Open University Geological Society Journal

Volume 33 (1) 2012
Stirling Symposium Issue

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ISSN 0143-9472
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OUGS Journal 33 (1) Edition 2012, printed by Hobbs the Printers Ltd, Totton, Hampshire

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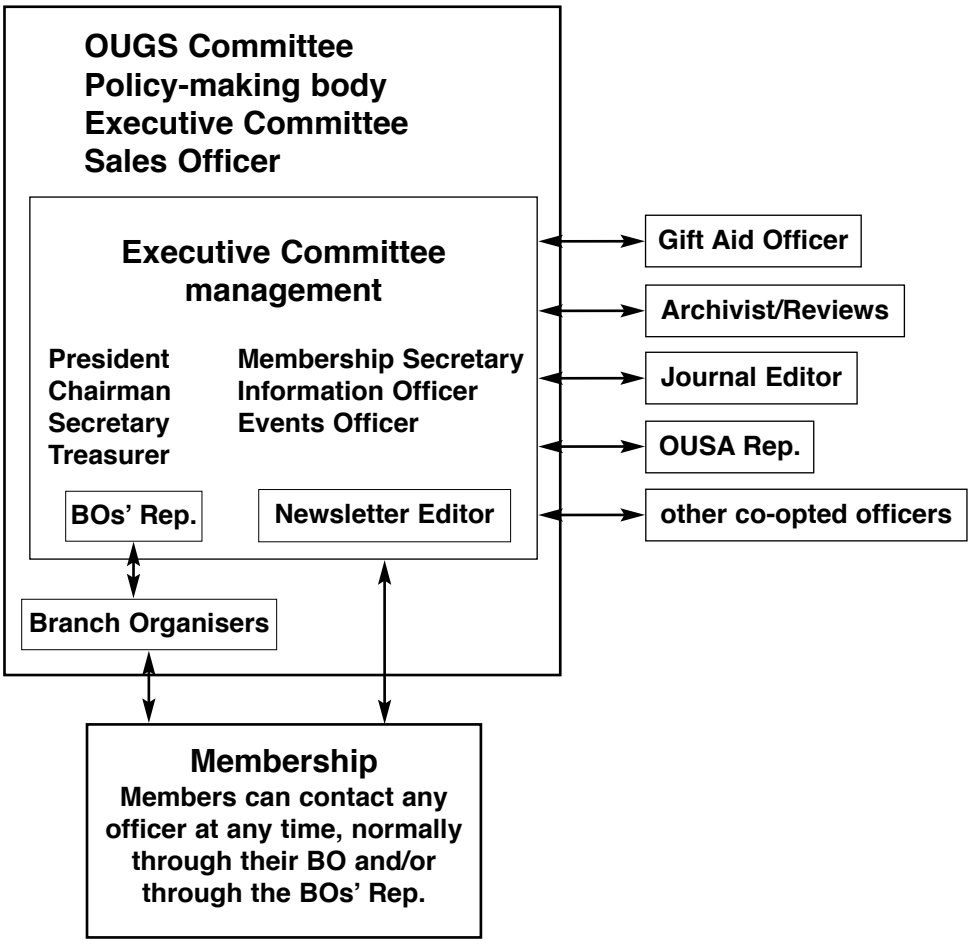

Editorial:

Dear readers,

First, I must apologise for the long delay in publishing this first part of Volume 33 of the OUGSJ. *Suffice it to say, that it is not possible to publish what one doesn't yet have; but that I think it has been worth the wait.*

This issue publishes the papers from our 2011 Annual Symposium, held in Stirling, 19–21 August 2011. Unfortunately, not all of the speakers at the Symposium have been able to complete a paper for our journal. For various reasons Dr Kathryn Goodenough (BGS, Edinburgh), Dr Simon Cuthbert (University of the West of Scotland), Dr Brian Bell (University of Glasgow) and Prof. Stuart Monro (Scientific Director, Our Dynamic Earth) were unable to write-up their lectures for us. In the case of Prof. Brain Bluck, owing to reasons beyond his control, his lecture had to be cancelled.

Therefore, I include here the publication of their abstracts from the Symposium programme, or in Prof. Munro's case, his statement, "I'm not sure that my summary at the end would make a very good paper as much of the substance is far better covered by the contributors themselves." PowerPoint slides are indeed of low-resolution regarding publication.

So, this issue begins with Dave McGarvie's most recent exploits in Iceland, exploring Grímsvötn's most recent eruptions and comparing them to other Icelandic volcanic activity.

Then various papers explore ongoing research on the orogenic events and their repercussions in Scotland, northern Ireland and the effects of Atlantic opening on dinosaur distribution and speciation.

Once again continued research proves to refine our geological interpretations, modifying earlier conclusions and proposing new explanations.

I think I speak on behalf of all OUGS Members — those who were present at the Stirling Symposium and those who could not make it, but enjoy reading the papers by the lecturers — for the co-operation and efforts of those speakers who found time to write up their papers and thus share their research with us.

— David M. Jones, OUGS Journal *Editor*

Expedition to the Grímsvötn volcano, Iceland

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[Editor's note: This was the Symposium presentation lecture, given by Dr Dave McGarvie]

Abstract

Grímsvötn is the most active volcano in Iceland with >60 known eruptions in the last 800 years. Grímsvötn is located in the centre of the 8100km^2 Vatnajökull glacier and typically produces basalts in phreatomagmatic eruptions. Magma-water interaction occurs when the eruptions quickly melt their way through 50–200m thick ice covering a subglacial caldera lake. Most of these eruptions have been relatively modest in size (0.01–0.1km^3 DRE), causing relatively minor fallout of tephra outside Vatnajökull. After a relatively quiet time during most of the latter half of the 20th century, a period of increased volcanic activity in Grímsvötn started in the 1990s, with basaltic phreatomagmatic eruptions occurring within the caldera in 1998 and 2004.

The 2011 eruption was therefore expected. It began at 19 UTC on 21 May. The plume quickly rose to 15–20km, forming a 50–100km wide umbrella cloud that was sustained until late on 22 May. Heavy fallout occurred in the districts 70–100km south of the volcano, where periods of total darkness with drifting ash closed roads and caused distress to the local population. Wind directions and plume transport varied somewhat during the eruption. After 23 May, the eruption was relatively minor, with fallout mostly confined to the Vatnajökull glacier. The eruption ended on May 28.

Most of the magma was erupted in the first two days. During this period strong northerly winds were dominant at low altitude, carrying the tephra towards south, while the top part of the plume first drifted eastward and later northward. Most of the fallout after the first few hours came from the low eruption cloud, while the high plume was white in colour and with apparently low concentration of ash leading to only minor fallout. This eruption falls into a class of events that seem to happen once over 100–200 years, with previous large historical eruptions including 1619 and 1873. Preliminary estimates indicate that the eruption produced 0.6–0.8km^3 of tephra, roughly corresponding to 0.2–0.3km^3 DRE. Fallout was detected outside Iceland in Jan Mayen, the British Isles and Scandinavia. Seven distinct phases can be identified in the proximal and medial tephra stratigraphy, showing that the activity alternated between dominantly phreatomagmatic and magmatic, with the most energetic phases producing basaltic pumice.

The 2011 eruption of Grímsvötn demonstrates the ability of basaltic volcanoes to occasionally produce large sustained magmatically driven explosive eruptions. The dominance of fallout towards south, despite a high northward-drifting eruption cloud, demonstrates complex interaction not fully accounted for in common models of plume behaviour.

Introduction

This account deals with an expedition to the Grímsvötn volcano in July 2011, just two months after its May 2011 eruption ended. It was a special experience to observe at first hand the dramatic aftermath of a powerful basaltic eruption through a glacier. In addition, a tephra-covered ice cap is an ephemeral landscape and it was a rare privilege to see this. After the snows of winter, many metres of snow will have buried this new tephra layer and restored the ice cap to its normal appearance of a vast white wilderness.

First, a brief word on terminology. 'Tephra' is the generic term volcanologists use for all products erupted explosively from a volcano, from ash to bombs, and including rock fragments, which are often called lithics, torn from the conduit walls. Instead of 'lithic', the clumsy but more accurate term 'non-juvenile clast' is being pushed by some who spend a lot of time working on these rocks. The term 'ash' refers to clasts less than 2mm in size.

The main aim of the expedition was to gather information on proximal and medial tephra deposits. The medial deposits were important because by winter's end 6–10m of snow would have covered these forever. Work on the medial deposits (Fig. 1) involved: measuring tephra thickness, as this is used to create isopach maps, which in turn enable calculation of the total mass of material erupted; characterising the different layers so that these could be correlated with the thicker layers in the proximal deposits, as these enable the extent and volume of the different eruptive phases to be mapped. The proximal deposits (Fig. 2, *overleaf*) were important because these contain a complete record of every phase of the eruption, and they also hold the key to understanding why

Figure 1 A pit dug into medial tephra c. *120mm thick. Some differential melting of the underlying snow has taken place, creating a slightly uneven surface.*

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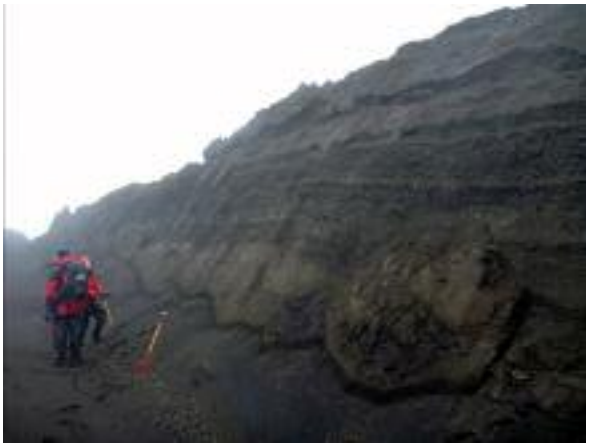

Figure 2 Proximal deposits c. *2km from the eruption crater (courtesy of John Stevenson).*

Figure 3 The huts on top of the eastern end of the Grímsfjall ridge, the only exposed part of the Grímsvötn volcano. From the huts to the ice plain below is c. *200m.*

this was such a powerful eruption. Work on the proximal deposits involved characterising the clast populations in the seven distinct eruptive phases, with particular emphasis given to understanding the role of magma–water interactions in controlling clast characteristics (such as vesicularity, morphology and size), and in identifying phases of the eruption where water was not involved. Fortunately the proximal deposits within the active Grímsvötn caldera will be exposed in future years, because although they will also be covered with snow by winter's end, continuous inflow of ice into the crater will open new crevasses and therefore expose new sections.

This paper, based on my lecture at the OUGS Stirling Symposium 2011, comprises two sections. First, a brief introduction to the Grímsvötn volcano and a short description of the 2004 eruption; and second, a description of the July 2011 eruption and expedition.

The Grímsvötn volcano

This ice-covered volcano lies in the western heart of the vast Vatnajökull glacier — Iceland's largest ice sheet. It lies more-or-less above the centre of the Iceland mantle plume, although as there is many a slip twixt mantle and surface, the presence of a mantle plume does not necessarily influence the compositions of erupting magmas. This is indeed the case, as the geochemistry of Grímsvötn's eruptives is no different to the geochemistry of tholeiites erupting throughout the Icelandic rift zones. But Grímsvötn is Iceland's most frequently erupting volcano (at least 70 eruptions in the past 1,000 years), and it erupts at least once a decade. So it seems reasonable to conjecture that this high eruption frequency may be related to the predicted higher production of melt near to a mantle plume. If this were the case, then it could be predicted that corroborating evidence would exists in the form of a 'dartboard'-like shape around the plume centre, with volcanic systems farther away from the bulls-eye of Grímsvötn showing progressively decreasing eruptive frequency. However, such a pattern is not observed, so the reasons for Grímsvötn's high eruption frequency must lie in the melt generation and melt storage systems beneath the volcano itself. It is not known why Grímsvötn erupts so frequently.

Grímsvötn is interpreted to comprise three calderas, the key word being 'interpreted'. Information extracted using ice-penetrating radar and other geophysical studies has identified three broad depressions beneath the ice, and although most geologists would require the production of *prima facie* evidence (e.g. faulting) before calling any depression a caldera, this evidence is currently buried beneath the ice at Grímsvötn. Nevertheless they have been called (and may actually be) calderas, but the point being made is that some interpretations are less robust than others.

Only one part of the volcano is exposed above the ice. This is the southern margin of the active (southernmost) caldera, which forms an east–west ridge called Grímsfjall (Fig. 3) that has a maximum elevation of 1,725m (5,659ft). As the rest of this active caldera is buried beneath the ice, there is an unanswered question as to why this southern margin is so topographically elevated. This highlights the fact that although we know much about Grímsvötn, there remain long-standing mysteries. On the eastern end of this ridge lie the sturdy huts (Fig. 4) that are used for just a few weeks each year by scientists, who carry out research in the area. The ridge has not been studied in detail, but it is apparent that it comprises various fragmental basalt units produced during subaqueous and subglacial eruptions, as well as the emergent (i.e. subaerial) phases of these eruptions. Immediately to the north of this east–west ridge lies the beating heart of Grímsvötn — an ice-covered lake. A moment's thought will lead you to conclude that sustaining an ice-covered lake in the middle of a glacier requires a heat source, and this is one of Grímsvötn's defining characteristics. The presence of a large high-temperature geothermal system is unquestioned (corroborated by the presence of active geothermal features on the Grímsfjall ridge), and this

Figure 4 The sturdy huts on top astride the Grímsfjall ridge.

geothermal system is driven by heat escaping upwards from a plexus of sills and dykes and other magma holders in the uppermost crust.

So, we have the unusual situation where a subglacial lake in a volcanic depression is capped by ice (up to 200m thick), and where the lake itself is sustained (and becomes enlarged) by a vigorous geothermal system powered by magma sacrificing its thermal energy. There is in fact an endless supply of ice available for melting, as ice is continually flowing into the depression, and therefore conditions exist for enlarging the volume of the subglacial lake exist. However, this is not a stable situation, as eventually the growing subglacial lake will become too large to be contained. When this happens either the water will flow over the lowest point in the bedrock rim of the caldera margin, or the water will lift and/or break through the ice seal at the lake margins. In fact, it is the breaking of the ice seal that occurs at Grímsvötn, and once the water starts to escape it does so extremely rapidly, travelling within embryonic subglacial tunnels and channels and enlarging them considerably before emerging at the glacier margin on Iceland's south coast 2–3 days after escaping, to form a glacial outburst flood known as a 'jökulhlaup'. In essence, such floods are not the direct result of volcanic activity, but instead are the result of prolonged melting of ice and of the storage of meltwater, followed by its sudden release.

Of particular interest to volcanologists is that the sudden draining of water from Grímsvötn has on a number occasions triggered a small volcanic eruption, suggesting that the sudden release of mass from above a sensitive magmatic plumbing system has been sufficient to allow the upward release of a packet (or packets) of basaltic magma. This is what happened in 2004, and a brief account of this small Grímsvötn basalt eruption follows, as this contrasts nicely with the much larger eruption of 2011.

Grímsvötn: the November 2004 eruption

This small eruption was a fairly typical Grímsvötn eruption, and because it was fairly recent and small it was particularly well studied. Improved monitoring of the volcano by Icelandic scientists during the past decade meant that two important points were known: first, that there had been gradual uplift of the volcano as fresh magma entered the subsurface plumbing system, and so the volcano was primed for eruption; and second, that the subglacial lake was very full and ready to burst. An eruption was expected.

What happened next was fascinating. The subglacial lake drained rapidly, lowering its water level by *c.* 15–20m. The flood water reached the glacier snout three days later and spread over the sandur plain. Six days after the escape of water from Grímsvötn a small volcanic eruption started, initially as a short fissure eruption perhaps 200–300m long, but soon focusing on just two vents. Initially, the erupting magma had to break through *c.* 200m of overlying ice before it could reach the atmosphere, and records show that this took only half an hour. This was the start of the formation of a cauldron (crater) in the *c.* 200m thick ice, and at the end of the eruption an elongate ice cauldron some 700m long and 500m wide had been formed. It is estimated that the formation of this cauldron required about one-third of the total thermal energy released by the eruption. This point illustrates beautifully just how ice modifies eruptions — because consider for a moment: what would have happened to this thermal energy had it not been sacrificed in melting ice?

This was a small eruption (*c.* 0.06km^3), characterised by a weak and steam-rich plume only 8–9km high, which was bent northward by the strong southerly winds. However, there were brief periods when the plume was stronger and rose higher (*see below*). Most of the time the weak plume dominated (i.e. the mass discharge rate was fairly low), leading to the production of a great deal of steam created during intense water–magma interactions, and characterised by a dominance of pale-coloured (white-cream) convecting clouds in the plume. However, when magma discharge rates increased, the core of an eruption column was shielded from interacting with water, and at such times the plume gained in strength. These periods of activity produced distinctive 'continuous uprush' of tephra in noticeably darker eruption columns. Essentially, as less thermal energy was being sacrificed during magma–water interactions, it meant that this energy could go instead into sustaining a higher plume; and during such periods the plume reached as high as 12km, but only for an hour or so.

These facts help to answer the question posed in the previous paragraph. It was observed that when two vents were erupting simultaneously, one was erupting mostly steam while the other erupted mostly tephra. After the first three days the eruption diminished in energy considerably, and after this the plume rose no more than *c.* 2km above the vent. The eruption ended almost exactly a week after it started, and at the end of the eruption a small tephra ring (tuff cone) some 200m in diameter had formed within a water-filled 700m by 500m ice cauldron.

Grímsvötn: the May 2011 eruption

First, a few headline facts and figures before describing the July expedition:

- An eruption was expected, but it happened earlier than anticipated.
- It was a large eruption (*c.* 0.2–0.3km3), some 3–5 times bigger than the 2004 eruption.
- This was Iceland's most powerful explosive eruption since the Hekla 1947 eruption some 64 years ago.
- More tephra was erupted in the first day of the eruption than in the entire 39 days of the 2010 Eyjafjallajökull eruption.
- Such a powerful eruption took everyone by surprise: it was definitely not expected.
- Subsequently, a careful search of the historical records suggests that such large eruptions occur occasionaly at Grímsvötn, with the two most recent ones being in 1873 and 1619.
- The unusually high mass discharge rate (technical term for eruption rate) meant that an atypically high eruption plume could be sustained, and so the eruption plume was able to reach to 15–20km.
- Most of the tephra was erupted during the first two days.
- The eruption lasted a week, the same duration as the previous, 2004, eruption.
- At the end of the eruption a sizeable lake started forming as water flowed into the *c.* 100m high ice-walled crater that was created during the eruption (Fig. 5, *overleaf*).
- Heavy tephra fall south of the volcano led to periods of total darkness and considerable anxiety to Icelanders living on the south coast (75–100km from the eruption).

For various reasons I'll not describe in detail here, although the Grímsvötn eruption injected a huge amount of ash into the

Figure 5 The May 2011 eruption site. Before the eruption there was no lake — just a sheet of ice.

atmosphere in a short period, it caused less chaos for UK air travel than the much smaller 2010 Eyjafjallajökull eruption did. However, in a lovely touch of irony, the Grímsvötn ash cloud drifted over Glasgow on the day I was due to fly from there to Iceland on fieldwork, and, as the Met Office had predicted high ash concentrations, Scottish airspace was closed and my trip to Iceland was delayed by three days.

Apart from the safe 'tourist' areas on the ice caps, Icelander's avoid travelling on the ice caps in the summer because snow bridges across crevasses are either absent or very weak, and because uneven melting of the slushy surface means travel is slow and uncomfortable. But it was decided that an expedition should go the crater in late July with the aim of gathering evidence and samples that would help us understand why this eruption was so powerful. And I was invited to join the expediton.

So a team of nine, comprising two driver-mechanics and three scientists from the University of Iceland and the Iceland Glaciological Society, plus four foreign scientists (two Jocks, a Finn and a Kiwi), set forth on two specially equipped jeeps. The little jeep (Fig. 6) had only 36in tyres and the big jeep (Jöklarauður, the 'glacier horse') had 46in tyres. These tyres are deflated to very low pressures and spread in a rather alarming manner, so that they spread in a rather alarming manner, but in doing so they spread the weight of the vehicles and thus aid their passage across the glacier (Fig. 7). The big jeep (Fig. 8) towed a trailer on which the main item of scientific equipment was a freezer powered by a generator. (Yes, we took a freezer onto a glacier — more later.) At one of the 'comfort' stops I took a look at our location on the map and got a jolt when I realised that beneath my feet was 750m (*c.* 2,500ft) of solid ice.

My grinning Icelandic colleague said that in early spring, our 70km route across the ice to Grímsvötn can take as little as 1.5 hours. This was after we'd been on the ice for 9 hours, still had 1km to go up a crevasse-crossed ice slope to the huts, and had just spent the last hour hauling the little jeep out of two crevasses (Fig. 9, *opposite*). The reasons for the slow journey was that during the spring and summer the glacier gets a thin coating of windblown ash, which becomes unevenly distributed as it tends to collect in small hollows. The dark ash absorbs sunlight and then releases its heat to the underlying snow, promoting melting. So by late summer, when we were on the glacier, it was a very uneven surface and we could drive no faster than 10mph — and even that was punishing on the jeeps and their inhabitants.

Worse was to come as we started crossing the fringe of the new tephra deposit from the May eruption. The main axis of tephra dispersal was south, and as we approached the tephra blanket from the east we found that in the two months since the eruption what was once an even blanket of tephra had become transformed by differential melting into a field of tephra-covered cones *c.* 0.5m high (Fig. 10, *opposite*). As we progressed farther east the tephra became thicker, and the differential melting became greater (both because thicker tephra protects the

Figure 7 Crossing the Vatnajökull glacier with 800m of ice beneath the tyres.

Figure 6 The little jeep with driver-mechanic — note deflated tyres to assist travel over the glacier.

Figure 8 The big jeep, with 46in tyres.

Figure 9 Little jeep noses into a small hidden crevasse as a weak snow bridge collapses. It only took 10min to jack the front up, reverse off, and escape (courtesy of John Stevenson).

Figure 11 View westward from the huts across the tephra plateaus, over which the 'road' was built, to the thicker tephra along the fallout dispersal axis. Our vehicle tracks can be seen on the thicker tephra.

underlying snow from melting and because where it had thinned, melting had been enhanced); and this produced a landscape of linear and tephra-covered plateaus 2–2.5m high (Fig. 11) with intervening valleys of ice and snow. The ridges look like they are composed entirely of tephra, but a swift kick would reveal that it was only 30–40mm thick. Even farther east there was blessed relief, as the much thicker tephra (nearly 2.5m thick only 3km from the eruption site) had completely protected the underlying snow to leave a smooth surface on which one could drive at 90km hr^{-1} (Fig. 12).

But we didn't know this as we toiled up to the huts, which we reached some 12 hours after we had set off. These sturdy huts are perched on the only exposed and solid rock in the area, which is the southern ridge — called Grímsfjall — of the active caldera. Perched on the ridge crest at 1,719m elevation (5,640ft), the huts are comfortable, heated by geothermal activity, and, if one wishes, one can even share the toilet with a friend (Fig. 13, *overleaf*). There is also a sauna, and we followed Icelandic mountain tradition by wearing no clothes. If you want a shower, then you also get a workout, as the water has to be pumped by hand. Having a close friend to pump while you wash (it is after all a small shower cubicle) would of course make the shower a more pleasant experience, but although sharing the sauna was commonplace, nobody seemed comfortable sharing the shower (or the toilet for that matter). An important safety point was made about being in this location: except for going to the hut containing the toilet, shower and sauna, nobody was to go out of the hut on their own. When people did go out they were required to tell someone exactly where they were going and not to deviate from this. This 'rule' is because there are deep and wide crevasses in the glacier to the south of the huts, and a *c.* 200m high cliff to the north of them.

The two main scientific aims have been described earlier, and basically involved logging a type section of the proximal deposit and digging pits in the medial deposit to establish tephra thickness and to correlate medial layers with proximal layers.

Day 1 in the field focused on the first aim. It was decided not to take the vehicles, as repairs were necessary after the battering they had taken getting us to the huts. So it was a miserable 5km hike from the huts to the proximal exposures on the southern rim of the crater, over a dark tephra-covered landscape, done in driving rain and cloud, with visibility down to 20–30m and the temperature maximizing at 2ºC (Fig. 14, *overleaf*). This is not untypical weather for those used to working in Iceland, but the Hawaii-based Finnish PhD student struggled, so it took us three hours each way. It was worth it though, as the 5–6m sections exposed on crevasses were superb. Vapour was escaping from numerous cracks in the tephra deposit because it was still cooling down. (If your hands got cold you just stuck them into one of the steaming cracks.)

Figure 10 Differential melting of the underlying snow by uneven thicknesses of thin 2011 tephra led to tricky driving.

Figure 12 Thicker tephra (>160mm) forms a smooth surface over which fast driving is both possible and pleasant.

Figure 13 The unusual toilet at Grímsfjall. It was never explained why there were two. Both empty into the same large container mounted on skis.

Figure 14 The 5km hike to the proximal deposits at the crater edge — GPS was useful.

In the proximal deposits seven major layers were evident, three of these being of golden-coloured pumice with an unusually high abundance of small bubbles for basaltic pyroclasts. Now, this was exciting, because it told us that the magma was erupted from depth so quickly that the gas wasn't able to coalesce into larger bubbles, but had to form many small bubbles. The reason for this is that it is thermodynamically easier for a new bubble to join an existing bubble than to form a bubble of its own, so an abundance of small bubbles indicates a lack of coalescence time. The presence of numerous small bubbles also told us that the magma packets that erupted this unusual pumice hadn't even seen a sniff of water or ice. This was nicely consistent with such a powerful eruption, where it would be expected that only the outer fringes of the eruption plume would interact with any water or ice. If the past few eruptions could be described as Grímsvötn puffing gently, this 2011 eruption was Grímsvötn roaring. It was also evident from what was in the proximal deposits that multiple vents had been erupting at the same time, which corroborated observations made during the overflights that took place during the first two days of the eruption.

On *Day 2* the weather was worse and the Icelanders said it was more sensible to stay in the hut — and who were we to argue? So we had a morning of scientific discussion and got the ropes and hardware out to practise crevasse rescue techniques from the bunk beds. Discussion led to the conclusion that we needed to use the vehicles on subsequent days to maximise field time, and the suggestion was made that we should build a 'road' across the tephra plateaus until we reached the thicker tephra along the dispersal axis (Fig. 15), where driving was smooth and fast. So five of us went out in cold, windy and wet weather and built the road, which basically involved mapping a route, then filling in hollows and softening the plateau edges to form gentler ramps for the jeeps. Tiring work, but it made the evening wine taste all the finer (Fig. 16).

Day 3 was cloudy, but we drove over the newly-formed road to the southern wall of the crater and split into two teams — one logging the thick proximal deposits and the other roaming in the little jeep and working on the medial deposits. I was in the medial team, and experienced the fun of driving at 90km hr^{-1} on a tephra-covered glacier. However, to start with we all worked together as one team, as we wanted to dig a pit some 8km from the vent, along the dispersal axis, to check that the layers here correlated with the seven layers we'd identified in the very proximal, 6–8m thick sections. The layer here was only 1.9m thick, and one would imagine that digging through this to the pre-eruptive glacier surface below would be easy — and it would have been, except for the four frozen layers that had concrete-like properties and that broke shovels and blunted our steel bars. Some of these frozen layers formed when steam that was erupted along with the tephra had turned to ice around the tephra particles, which froze together when they fell to the surface. Normally it's heat that bonds volcanic

Figure 15 Return to the huts after building the 'road' across the tephra plateaus (courtesy of John Stevenson).

Figure 16 It's a jolly life in the Grímsfjall hut — assisted by ample food and alcohol.

Figure 17 Why we took a freezer onto a glacier: On top of the glacier surface lies the first products of the May 2011 eruption — tephra and ice hailstones. Little is known about them. They need to be kept cold.

Figure 19 The northern edge of the water-filled ice cauldron, which is the site of the May 2011 eruption. Ice flows continually into the cauldron and eventually the lake will be covered with ice and revert to being subglacial.

particles together, so it was somewhat quirky that cold was the bonding mechanism here. And this is why we took a freezer onto a glacier, because these frozen layers are unusual and poorly understood (and also change with time), and to preserve original textures they needed to be kept in sub-zero conditions (Fig. 17). Ergonomics and the needs of science determined that our deepest pits (*c.* 2m deep) needed to be *c.* 2m long and just over shoulder width. They looked remarkably like graves. It took eight people about an hour and a half to dig one of the 2m deep pits (Fig. 18).

Day 4 was the final field day, and we had not yet seen the main crater. But the weather was improving and so was our optimism. We only knew where the crater was because frequent deep rumbles told of the collapse of its ice walls a few hundred metres away. Normally the crater is covered with 150–200m of ice, but the eruption had melted this to expose a churning lake with steep and unstable ice walls (Fig. 19), and on the lake itself floated rafts of pumice with ice bergs gathering around its margins. This is what we saw when we got there, and it was quite impressive. On this day I was in the medial team again and we were working against the clock to dig and log as much as possible. We were acutely aware that this was a once-only opportunity to collect this information. The ease of digging tephra pits just a shovel blade deep (Fig. 20) was offset by the much greater time it took to travel over the thinner tephra deposit, as we were once again into the land of tephra pyramids and plateaus, and slow driving.

Day 5, the morning of departure, greeted us with a blizzard (Figs. 21 and 22, *overleaf*). We looked forward to an incident-free drive of about six hours back across the ice. However, just 1km from the huts the big jeep slipped off the planks while crossing a crevasse and in trying to get it out the front left axle snapped (Figs. 23 and 24, *overleaf*). So we sent five of the team back to the huts to keep warm while four of us spent three hours chipping away the ice to form a ramp up which the broken wheel could move. After this it only took 45 minutes to replace the axle. We were back on the road again, only for the frame on the big jeep to snap. So one of the drivers got underneath the jeep with the radio and gave instructions to the other driver until the separated components were together again. Then we got out the portable generator, fired it up, and within an hour the frame had been welded together again (Fig. 25, *overleaf*).

I was struck by three points: first, that long experience had taught the Icelanders the need to be self-sufficient on the ice with respect to repairs; second, that when I was first told that on such trips they get the driver-mechanics sorted first and then get the scientists, I thought that this order was odd, but now I understand the wisdom of this; and third, it makes me wonder why I have to wait a week before my garage can do a simple

Figure 18 The deeper tephra pits were somewhat like graves.

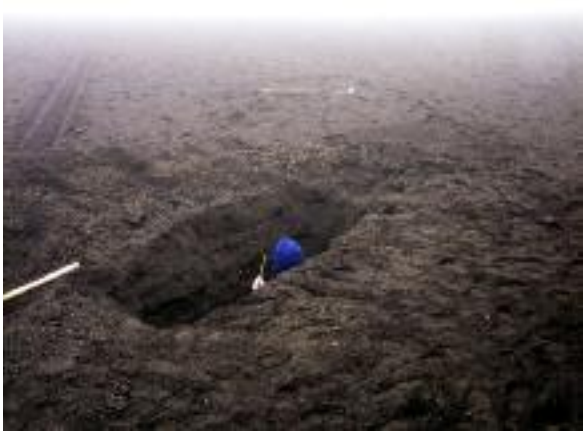

Figure 20 Tephra pit in medial area, showing different layers that can be correlated with the thicker layers in the proximal tephra deposits.

Figure 21 The view from the Grímsfjall toilet on the day of departure, as the blizzard started.

Figure 22 Packing in a blizzard on the day of departure — icicles forming.

repair to my car. For diffedrnet reasons, it took us 12 hours to travel to the huts from the edge of ther glacier and it also took us 12 hours to travel back.

Like most geology projects, fieldwork provides an essential framework (ground truth) and fuller understanding gradually develops through follow-up labwork and serious thinking. So there is a lot of follow-up work being done on the samples collected on this trip, and we have notebooks filled with measurements and observations.

If I were to be asked to go back to Grímsvötn again, I probably would, as I have a specific project in mind that involves working on the proximal deposits of both the 2011 and the 2004 eruptions. But the more I go to Iceland the more I find interesting problems that need solving, and it's a tough job sometimes having to decide which ones to work on. It's a nice decision dilemma to have though!

Figure 23 The big jeep crossing a crevasse in the standard manner, using sturdy planks with ice and snow packed around them. Driver is guided by radio.

Figure 24 The big jeep slipped off the planks into a crevasse — breaking its front left axle.

Figure 25 The big jeep's broken frame was welded back together again in less than an hour, in a blizzard!

The Laurentian basement of the North-west Highlands: the first two-thirds of Scotland's geological history

Kathryn Goodenough

British Geological Survey (Edinburgh)

Abstract (only)

The oldest rocks in Scotland were formed c. *3Ga ago, during the Archaean Era, and are found within the Lewisian Gneiss Complex of the North-west Highlands and the Outer Hebrides. Parts of the complex were subjected to two episodes of metamorphism and deformation during the Archaean Era, as well as several periods of magmatism. These rocks are well exposed and have been intensively studied, but their geological history is so complex that many questions about their formation remain unanswered. This talk looked at the early history of the Lewisian, and considered how the protoliths of the gneisses were formed, when they were formed and what happened to them subsequently. One of the key developments in Lewisian geology in recent times has been the recognition that the gneisses were not formed as a single piece of contiguous crust; instead, they developed as a series of separate terranes. Dr Goodenough looked at the evidence for terrane hypothesis, and considered what that can tell us about when modern plate tectonic processes must have started.*

In the early Palaeoproterozoic, the Lewisian gneisses lay within an area of continental crust that was undergoing extension, with emplacement of the widespread Scourie Dyke Swarm. Later in the Palaeoproterozoic, they were again affected by deformation, metamorphism and magmatism during a series of events generally known as the Laxfordian; Dr Goodenough considered the tectonic processes that caused these events. At the same time, substantial amounts of new crust were generated. That new crust is exposed today on South Harris, around Loch Maree, and in Islay, but can be linked with extensive areas of Palaeoproterozoic crust in Greenland.

In the North-west Highlands, undeformed Meso- and Neoproterozoic sedimentary rocks of the Stoer and Torridon groups overlie the Lewisian Gneiss Complex. Dr Goodenough looked at these units and considered their potential lateral correlations with other rock units around the North Atlantic. It has recently been proposed that the Stoer Group, which is Mesoproterozoic in age, includes a meteorite impact layer — but this is controversial.

Lastly, Dr Goodenough gave a brief overview of the Cambro-Ordovician sedimentary sequence that rests unconformably on the Torridon Group.

Grenville to Valhalla: Mesoproterozoic to early Neoproterozoic events in the Moine and Grampian blocks

Simon Cuthbert

University of the West of Scotland

Abstract (only)

The Northern Highland Block, west of the Moine Thrust and north of the Great Glen Fault, is dominated by the sediments of the Moine Supergroup, with their long history of deformation and metamorphism. Many years of research have led to some key developments in the fields of tectonics and metamorphism. The Moines are built from three stratigraphic units contained within a stack if large thrust nappes. The Moine Thrust is a fundamental structure that carried the entire Moine nappe pile more than 100km westward, over the Hebridean foreland gneisses and their sedimentary cover during the 'Scandian' continental collision in the late Silurian. Within each nappe, the Moines rest upon slices or infolds ('inliers') of rocks akin to the Lewisian gneisses of the Hebridean foreland. The Glenelg–Attadale inlier, at the base of the Moine nappe, preserves evidence for pre-Moine history, with the only well-preserved British eclogites (high-pressure, high-temperature metamorphic rocks associated with subduction and crustal thickening).

The Glenelg rocks comprise one of the few Precambrian high-pressure metamorphic terrains worldwide. The Moines were most likely derived by erosion of the rising Grenville mountain belt, dated c. *1100Ma. During their post-depositional evolution in the Neoproterozoic, they have been intensely deformed and metamorphosed by an episode of basic magmatism associated with granite formation at 870Ma, followed by crustal thickening, metamorphism and migmatite formation between 820Ma and 790Ma (the 'Knoydartian Orogeny'); by further granite intrusion at* c. *600Ma (rifting of the Iapatus Ocean); by deformation and metamorphism of eastern parts of the Moines* c. *470Ma; and by the collision of Baltic and Laurentia* c. *420Ma. These events led to thrusting and formation of nappes — the Moine Thrust — in the late Silurian.*

The 'Badenoch Group' of metasediments in the Grampian Block, south of the Great Glen fault, bears close relationships to the Northern Highland Moines in rock assemblage and history. Their amphibolite mineralogy, in particular, indicates an early phase of post-Grenville crustal thickening, or even transient subduction, probably before the deposition of the Grampian group. The Moines and Badenoch Group form part of a much wider realm of Neoproterozoic clastic basin evolution and subsequent tectonism that also spanned east Greenland, northern Norway and Svalbard. This basic evolution and tectonism were generated during the assembly of a late Mesoproterozoic supercontinent — Rodinia — during which the combined continental mass of Laurentia, Greenland and Baltica collided with Amazonia. This collision raised the giant Grenville–Sveconorwegian mountain belt, which shed its sediments into adjacent basins. Erosion of these mountains created the quartz-rich rocks characteristic of the Scottish Northern Highlands.

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Book review

Burbank, Douglas W., and Anderson, Robert S. 2012 *Tectonic Geomorphology* (2nd edn). Oxford: Wiley-Blackwell (ISBN 978-1-44433-887-4; paperback, 454pp; £51.50)

This appears to me to be a remarkably fine textbook on an important, if rather scary-sounding, subject. But we are all of course surrounded by landscapes moulded by both tectonic and geomorphological forces. Yet while the depositional processes that originally laid down the rocks, and the Quaternary processes that have resulted in the present geomorphology, are frequently brought to our attention, the tectonic ones tend to be less so.

This book deals with areas where tectonic processes are currently very active, not mild and occasional as in Britain. But the vast and increasing array of insights from these areas into the interplay between forces, basically, that construct new features, and those that rework them, must be to some extent transferable to our local studies of more ancient faults, mountain building and deformation.

The second edition is needed because an "explosion of research" over the last decade "has begun to generate a new perspective on the interactions of tectonics with surface processes". Readily available, high-resolution digital topography, processes such as Lidar (also invaluable to archaeologists), geodetic and seismological arrays (such as EarthScope), space-based observations, advances in chronologic methods, improved physics-based understanding of processes, and the use of models have all contributed.

A striking feature kept from the first edition is that there are chapters on the relations between tectonism and geomorphology on different time scales — Holocene, Late to mid-Pleistocene, Late Cenozoic — because "the tectonic and geomorphic information that can be extracted from a landscape varies as a function of time". Each chapter has a useful and readable summary: Introduction; Geomorphic markers; Dating methods; Stress, Faults and folds; Palaeoseismology; Rates of erosion and uplift; Holocene; Late to mid-Pleistocene; Late Cenozoic; and Numerical modelling of landscape evolution. However, neither volcanic areas nor the sea floor are treated.

There are 32 pages of references; the index lists processes and geological concepts, but not locations. The figures are numerous (many more than in the first edition) and in a clear uniform style. A companion website, www.wiley.com/go/burbank/geomorphology, makes it possible and easy to open PowerPoint programmes (by chapter) of all the figures, incudling some in colour (which they are not in the text), the 13 colour plates and the tables. This feature provides a remarkable resource for anyone wishing to have teaching aids.

This is definitely a book worth taking a look at by any member; and one worth trying hard to come to terms with if aspects of this important subject really interest you.

— Philip Clark, MA (Oxon), BSc Hons (Open)

Book review

Harvey, Adrian 2012 *Introducing Geomorphology – A Guide to Landforms and Processes*. Edinburgh: Dunedin Press (ISBN 978-1-90671-632-5; paperback, 124pp; £9.99)

Adrian Harvey was Professor of Geology at Liverpool University and in this book he explains the processes that lead to the landscape looking the way it does. The book sits at the 'physical geography' end of geology, and while it has little that will be novel to readers who have completed the OU secomd-level general geology course it adopts a top-down systems approach that will get you to direct your geological knowledge to observe and understand geomorphological processes — and thence the scenery around you — more deeply.

The book measures 165mm × 195mm, has 124 pages, plenty of colour photographs and diagrams and a good card cover.

The first section (15 pages) introduces the reader to geomorphology explaining its concepts, the spatial and temporal scales on which it operates and the driving forces that underlie it — familiar geology so far. Two further sections, each of similar length, examine the effects of these — firstly on a global and then on a regional scale. This is where the book starts to get you focussing better on your geological knowledge to understand the landscape.

The next and major section, which makes up almost half the book, considers geomorphology on a local scale. We mainly recognise landforms and understand the processes that create them on this scale. This section is the guts of the publication and explains each of the main systems at work: weathering, slopes, and fluvial, aeolian, glacial and coastal systems. This section describes in some depth how each of these systems functions and the end results it leaves behind in the landscape. Maths are avoided and there is only a little physics and chemistry. Inevitably, much of the geology is Quaternary, mostly Holocene. Here is a subject where the devil is in the closely observed detail and there are many well-chosen photographs and diagrams to bring the items under discussion to life.

There follows a short section on the integration of timescales and landscape evolution, essentially case studies using and extending some of the lessons from the previous section to analyse landscapes in Cumbria and in south-east Spain. After this there is a short section on the interactions between geomorphology and society — the effects of man, some geohazards, environmental planning and research. Finally, there is a useful selection of further reading, and an excellent ten-page Glossary explaining the many technical terms that have been highlighted in the main text.

In summary, an accessible book to get you into geomorphology.

— Bob Morley, OUGS East Scotland Branch

Plates, dates and rates: the context of Dalradian evolution

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Abstract

The main features of the stratigraphy, sedimentology and structure of the Dalradian Suergroup have been known for several decades. These features are briefly reviewed within the context of the crustal evolution of the region.

The more contentious issues that have been the subject of recent research include (a) the relationship of the Dalradian to the underlying basement and hence the date of the onset of Dalradian depositon; (b) the nature and age of the stratigraphic top of the Dalradian and its relationship to the overlying units; (c) the identification and correlation of Dalradian tillite units with dated Neoproterozoic tillites worldwide; and (d) the plate tectonic context of the Dalradian terrane from the start of deposition to the culmination of deformation.

Many issues remain to be resolved, but the search for a consistent evolutionary picture is discussed, aided by a consideration of what are sensible rates for geological processes.

Introduction

The Dalradian Supergroup is a thick assemblage of metamorphic rocks, largely of Neoproterozoic age, which runs across Scotland and Ireland from Shetland to Connemara (Fig. 1). The term was introduced by Sir Archibald Geikie in 1891 in a Presidential Address to the Geological Society of London. However, he did not define exactly what he meant by the term, a fact that caused some subsequent confusion. The geological maps of the time show much of the detail in the Dalradian Terrane that we are familiar with today: a variety of rock-types including limestones, quartzites, slates and metabasites, outcropping in bands with Caledonoid trends. From the 1890s to the 1930s much of the ground in Scotland was mapped by the Geological Survey. This showed that the area was structurally complex, the rocks being disposed in large-scale, often flat-lying, folds. A major step forward was made in the 1930s when Bailey (1930) popularised the idea of using sedimentary structures to determine the stratigraphic way-up and hence to disentangle the stratigraphy and structure. Shackleton's (1958) concept of fold-facing led to another step change in understanding the structure and in 1979 Thomas synthesised the structure of the whole of the Moine and Dalradian Terrane between the Great Glen and Highland Boundary faults (Fig. 2, *overleaf*; Thomas 1979). His structural picture gave coherence to the evolution of the whole Dalradian Terrane, implying that the present geometry is the result of drastic shortening and thickening of what was a very wide sedimentary basin by a process that involved the underthrusting of massifs lying to the north-west and south-east of the orogen.

Our knowledge of the stratigraphy of the Dalradian has been slowly pieced together over the years by careful mapping and the correlation of distinctive lithologies (Fig. 3, *page 13*). A crucial consolidation of the stratigraphy came in 1970 when Rast and Litherland tied together the previously separate stratigraphies seen in the south-eastern part of the outcrop, from Islay to Perthshire, with that seen in the north-west in the Appin-Ballachulish area (Rast and Litherland 1970). By 1975 Harris and Pitcher (Harris and Pitcher 1975) were able to compile a gigantic stratigraphic correlation chart with no less than 100 formation names on it. Examination of this data shows that while it is possible to make long-distance correlations throughout the outcrop and to deduce general trends of stratigraphic evolution with time, there is a large amount of complexity and lateral variability, on all scales, within the Dalradian.

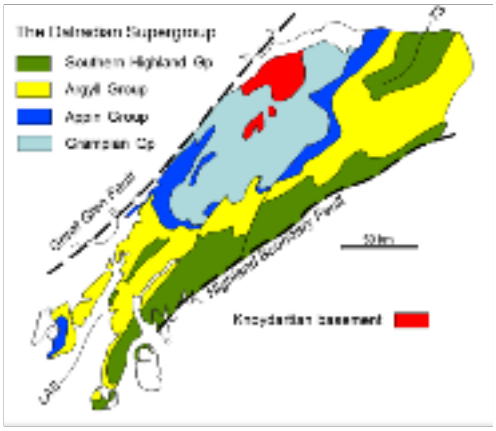

Figure 1 The Dalradian in Scotland, outcrop of younger units (granites, Old Red Sandstone) omitted. LAS = Loch Awe Syncline, TS = Turriff Syncline.

Detailed sedimentological analyses began with Spencer's (1971) study of the Port Askaig Tillite. Many sedimentological studies followed and these were reviewed by Harris *et al.* (1978) and updated by Anderton (1985). By then it was clear that Dalradian sediments were largely marine in origin and that shallow marine sediments predominated up to the middle of the Argyll Group and that deep water deposits dominated thereafter (*see* Fig. 3). This, together with the presence of volcanic and hydrothermal activity in the upper part of the section, led to the idea that Dalradian deposition took place in a basin that was progressively stretched or rifted, that as the rate of stretching increased subsidence started to outpace sedimentation leading to the development of deep-water environments and that stretching eventually thinned the underlying crust so much that large volumes of submarine volcanics were locally erupted (Fig. 4, *page 14*). Anderton (1982) thought that these volcanics were likely to be of a similar age to the Long Range Dykes in Newfoundland, dated at *c.* 600Ma, and that the volcanism dated the final rupturing of the continental crust and the birth of the Iapetus Ocean to the south-east of the Dalradian Terrane. Actual radiometric dating work on the Dalradian at this time was limited to dates of metamorphism. These showed that metamorphism and deformation had begun by the Arenig (early Ordovician), peaking at *c.* 470Ma, with uplift and cooling continuing into the Silurian. This event is referred to as the Grampian Orogeny.

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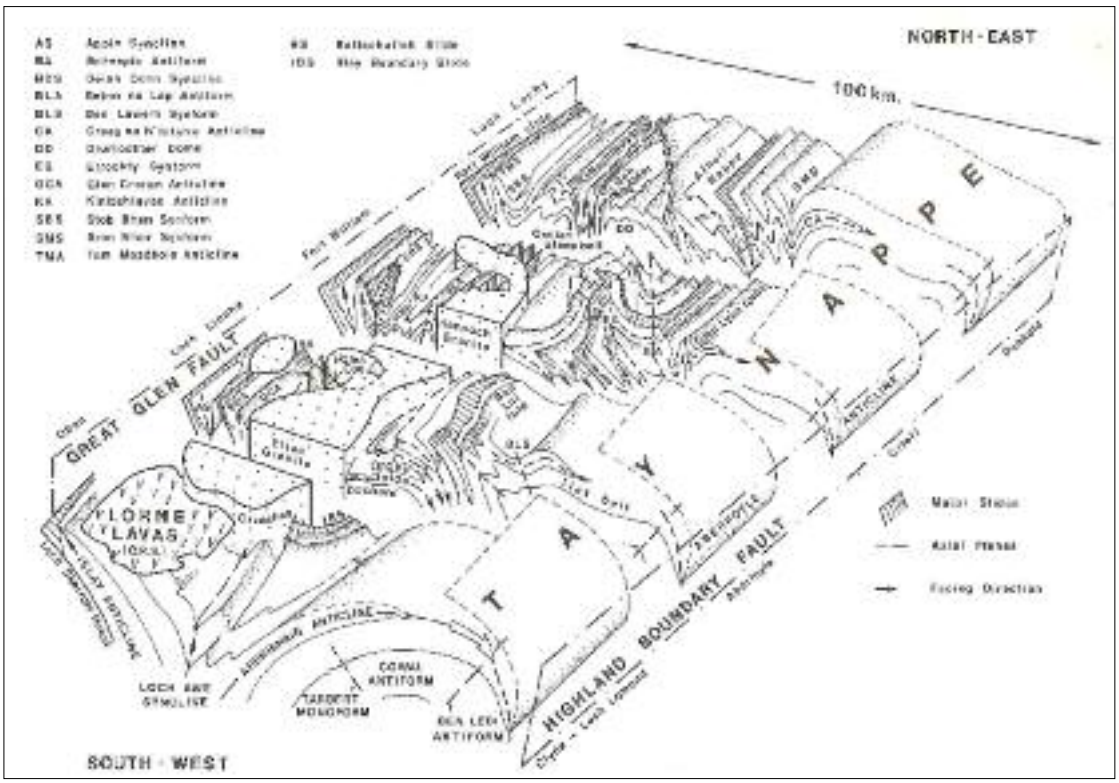

Figure 2 The structure of the Dalradian Terrane (from Thomas 1979).

So, by the 1980s a general consensus on the major aspects of the stratigraphy, depositional and deformational history of the Dalradian had been reached. However, many of the issues relating to its broader context were, and still are, subject to debate. These include the age and nature of both the base and the top of the Dalradian, the dating of key horizons within it and the plate tectonic context of its depositional and deformation episodes. These aspects are discussed below.

The base of the Dalradian and the nature of the Grampian Group

Up until the 1970s the base of the Dalradian was usually taken at the base of the Eilde Quartzite (base of the Lochaber Subgroup), the underlying psammitic rocks being referred to as 'Younger' Moines or Central Highlands Granulites. However, it had long been recognised that in places this boundary was either a normal sedimentary contact (Bailey 1934; Treagus 1974) or marked a lateral facies transition (Hickman 1975). Harris *et al.* (1978) proposed incorporating these Moine-like rocks within the Dalradian as a unit to be called the Grampian Group. The base of this unit was not, at that time, defined but subsequent work has shown that the Grampian Group unconformably overlies rocks that appear to have suffered a phase of Neoproterozoic deformation at *c.* 840Ma, now referred to as the Knoydartian (*see* Fig. 1). These rocks were called the Central Highland Division by Piasecki (1980) and the Dava and Glen Banchor successions by Smith *et al.* (1999).

The proposed incorporation of the Grampian Group within the Dalradian was not met with universal approval at the time (e.g. Lambert *et al.* 1982). Subsequent field work has elucidated a huge amount of detail about the stratigraphy, sedimentology and basin evolution of the Group. A range of fluvial, shallow marine, deltaic and deep-water environments has been inferred (Glover and Winchester 1989; Glover 1993) with deep basins, produced by rifting, being rapidly infilled by prograding sediment wedges (Glover *et al.* 1995). Robertson and Smith (1999) demonstrated that Grampian Group turbidites onlapped the margins of deep basins and then overstepped onto adjacent highs.

The style of sedimentation and basin evolution does appear to contrast with the picture of progressively increasing tectonic instability previously inferred for Dalradian evolution from Appin to Southern Highland Group times (Anderton 1985). New light has been cast on this issue by the the U-Pb dating of detrital zircons (Cawood *et al.* 2003). This shows a significant difference between the provenance of the Grampian Group and the rest of the Dalradian. The former shows hardly any zircon from Archaean sources, whereas it is common throughout the rest of the Dalradian. In this respect the Grampian Group shows more similarities with the underlying basement (Glen Banchor succession) than the rest of the Dalradian. Cawood *et al.* (2003) concluded that the Dalradian was derived from Laurentia and, more specifically, from the Greenland and Labrador regions. The source area of the Grampian Group sediments was either different, or there was significant uplift that, by the end of Grampian Group deposition, had unroofed the Archaean and exposed it to erosion. Either way, the change in the source detritus together with the change in depositional character and tectonic environment strongly suggest that something significant happened at the Grampian-Appin Group boundary. Glover (1993) speculated that this could be a decrease in subsidence and sedimentation rates. This would be consistent with an increase in drainage basin size, more intense weathering of detritus and greater variety of source material. Prave (1999) considered that the Grampian Group was more likely to be the molasse of the Knoydartian Orogeny than anything to do with Iapetus rifting. As such, one might still take issue with the inclusion of the Grampian Group within the Dalradian.

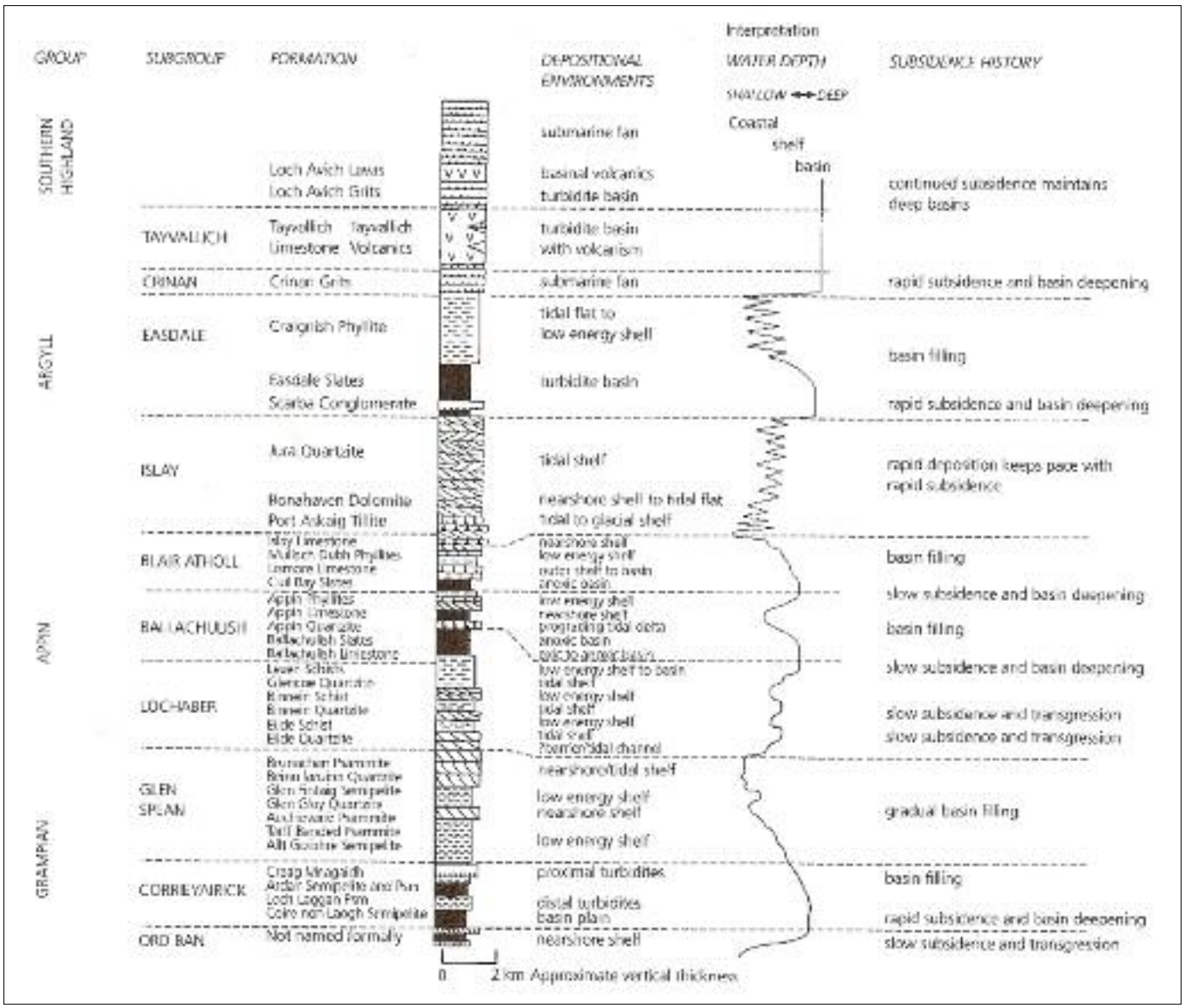

Figure 3 Type stratigraphy and interpretation for the Dalradian (modified from Anderton 1985): left-hand column gives Group names, next column gives Subgroups, third column gives Formations.

The age and nature of the top of the Dalradian

The relationship of the Dalradian to the Neoproterozoic units that underlie it and the general absence of fossils show that the bulk of the Dalradian is of late Neoproterozoic age. The question is, did Dalradian sedimentation continue into the Palaeozoic and, if so, how far? The youngest parts of the Dalradian succession in Scotland are found in the Loch Awe Syncline in Argyll, the Turriff Syncline area in Banffshire and adjacent to the Highland Boundary Fault (*see* Fig. 1). It is here that we would look for evidence for Palaeozoic ages.

There is a long history of biostratigraphical investigations on the Dalradian involving microfossils, trace fossils and macrofossils, none of which has proved to be entirely satisfactory either because of the wide stratigraphic ranges of the fossils or doubts about their affinity or context. A good example of this is the trilobite (*Pagetides*) found by Pringle (1940) in the Leny Limestone near Callander and generally accepted to be of late Early Cambrian age (Fletcher and Rushton 2007). The Leny Limestone has been included in the Highland Border Complex (Bluck *et al.* 1984), which would make it irrelevant to the dating of the Dalradian. However, Tanner (1995) contends that it lies within a succession of rocks that stratigraphically overlies the Ben Ledi Grits of the Dalradian Southern Highland Group and with which it shares an identical structural history (Fig. 5, *page 15*). This succession has been named the Trossachs Group (Tanner and Sutherland 2007).

If Tanner (1995) is right, the top of the Southern Highland Group cannot be younger than late Early Cambrian, by which time rapid sedimentation on the Dalradian continental margin had ceased. However, the very slow deposition — characterised by the black slates, limestones and cherts that are an important part of the Trossachs Group — could have continued here on a starved continental margin through the Cambrian until the beginning of the Grampian Orogeny in the Arenig. This would be consistent with events seen in the Northwest Highlands where the change from clastic to carbonate deposition may also date from the late Early Cambrian.

Microfossil data has proved to be rather equivocal, although Molyneux (1998) thinks that a sample from the Macduff Slate, near the top of the Southern Highland Group on the Banffshire coast, implies an Ordovician age. This is clearly incompatible with the Tanner's (1995) interpretation of the Leny Limestone and is also inconsistent with the presence of glacial deposits in the Macduff Slate, as is discussed further below.

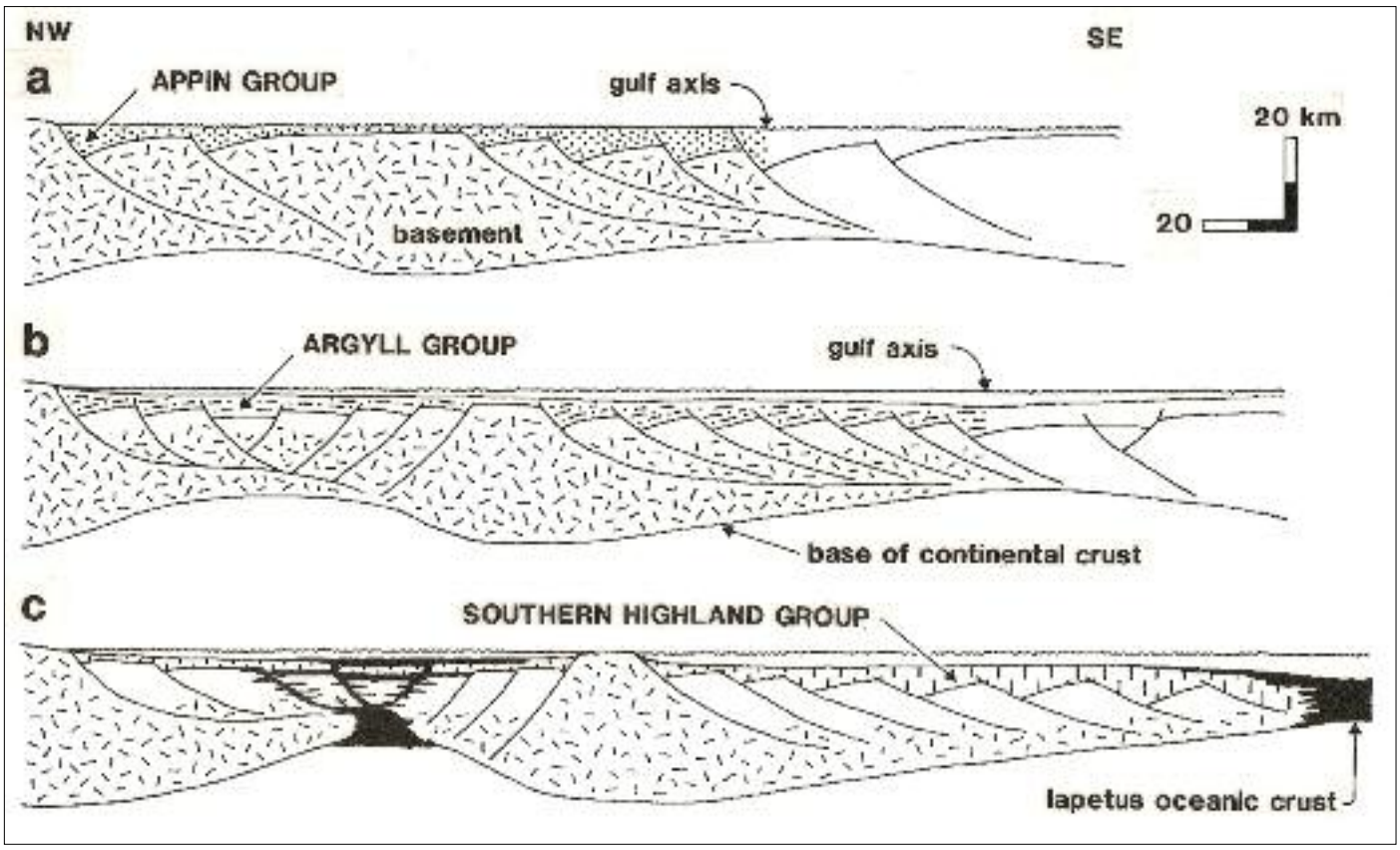

Figure 4 Dalradian crustal evolution (from Anderton 1985), showing progressive crustal stretching during the Appin and Argyll Groups leading, by the beginning of Southern Highland Group times, to the eruption of the Tayvallich Volcanics (black ornament).

Dating within the Dalradian

With the exception of the cases already mentioned, which are relevant to the dating of the top of the Dalradian, biostratigraphical data have not yet been able to refine the dating of the Neoproterozoic section. Trace fossils, stromatolites and microfossils have been found at several horizons but none have yet proved to be stratigraphically useful. Because of their subsequent metamorphism, extracting radiometric dates of deposition from Dalradian metasediments is also fraught with difficulty. The Tayvallich Volcanics, however, have been successfully dated with Halliday *et al.* (1989) deriving a U-Pb date of 595±4Ma on zircons from a subvolcanic intrusion, now bolstered by a 601±4Ma zircon date on tuffs by Dempster *et al*. (2002), both remarkably close to Anderton's (1982) guess of 600Ma based on stratigraphic analogies. A recent date of 660±10Ma on the Ballachulish Slate used a novel Re-Os technique (Rooney *et al.* 2011). The reliability of this technique is yet to be proved, notwithstanding the plausibility of the date.

Other dating techniques, involving stable isotopes, have been developed in recent years. The $^{87}Sr/^{86}Sr$ ratio of seawater is known to have risen from around 0.706 during the late Neoproterozoic to 0.709 in the Cambrian. Thus, measurements of 87Sr/86Sr ratios in Dalradian limestones, assuming that the limestones have captured the isotopic composition of the seawater from which they were extracted, can be compared with global curves. Using this technique, Thomas *et al.* (2004) concluded that the Dalradian must be younger than 800Ma and that the middle to upper Argyll Group cannot be much older than 600Ma.

Carbon isotope ratios in seawater are also known to have varied in a complex way during the Neoproterozoic. A world-wide $\delta^{13}C$ curve is being continually refined and if one has data from the limestones (Fig. 6, *opposite*) in a local stratigraphic sequence, it can be compared with the global curve to see where the pattern shows the best match. Part of the variation in the $\delta^{13}C$ during the Neoproterozic is attributed to variations in oceanic chemistry due to the climatic changes associated with ice ages. It has long been assumed that the Port Askaig Tillite (Fig. 7, *opposite*), which defines the base of the Argyll Group, correlates with other Neoproterozoic glacial deposits in many parts of the world. However, it is now known that there are three late Neoproterozoic tillite horizons resulting from major glaciations, the Sturtian, Marinoan and the Gaskiers. The latter two are quite precisely dated, the Sturtian has a wider uncertainty range (Table 1, *page 16*). As well as the thick and extensive Port Askaig Tillite, there are several other units in the Dalradian for which a glacial origin has been invoked. Within the Macduff Slate is a small but convincing outcrop of glaciomarine tillite (Stoker *et al*. 1999). In Lochaber, in the Appin Group, the Kinlochlaggan Boulder Bed has been interpreted as a tillite (Treagus 1969). In Donegal, Condon and Prave (2000) have described glaciomarine tillite horizons from the Southern Highland Group and McCay *et al.* (2006) identified a tillite within the Argyll Group, the Stralinchy Conglomerate. They also follow Elles (1935) in interpreting the Loch na Cille Boulder Bed in Argyll as a tillite although, as it forms part of the Tayvallich Volcanics, Gower (1977) suggested that it is a volcanic breccia.

Prave *et al.* (2009) have derived carbon isotope data from the numerous, but stratigraphically widely spaced, Dalradian limestones and matched the resulting curve to the global late Neoproterozoic pattern. As a result of this they favour a correlation that equates the Port Askaig Tillite with the Sturtian glaciation and they dismiss the Kinlochlaggan Boulder Bed.

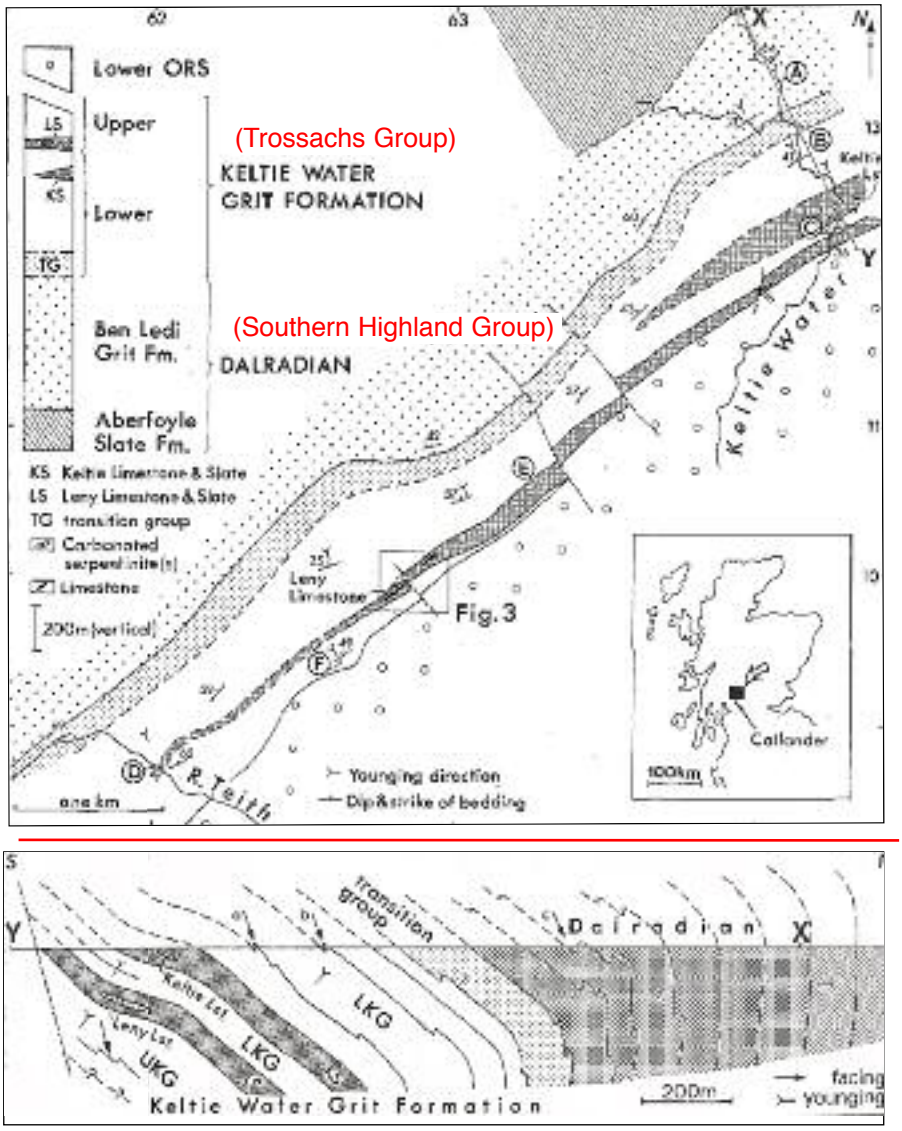

Figure 5 Location of the Leny Limestone outcrop, with cross section (red line) showing southward younging Southern Highland Group stratigraphically overlain by Trossachs Group (from Tanner and Pringle 1999).

They allocate the Stralinchy Conglomerate to the Marinoan and equate the Loch na Cille and Macduff Boulder Bed horizons to the Gaskiers.

The correlation of the Macduff Boulder Bed with the Gaskiers is interesting as it would imply that the Southern Highland Group in Banffshire is entirely Neoproterozoic in age. This is consistent with Tanner's (1995) interpretation of the Leny Limestone, although not with Molyneux's (1998) microfossil date. The tillites interpreted from the Southern Highland Group in Donegal could also be of Gaskiers age, even if the Loch na Cille Boulder Bed, which must be significantly older at *c.* 600Ma, is a volcanic unit, rather than a tillite.

The interpretation of the Stralinchy Conglomerate, in the middle of the Argyll Group, as a tillite equivalent to the Marinoan is crucial to the interpretation of the Port Askaig Tillite as being Sturtian in age (Prave *et al*. 2009). The alternative view is that Port Askaig and Kinlochlaggan horizons equate to the Marinoan and Sturtian episodes respectively (*see* Table 1). Both views suffer from the weakness that while there is one thick, extensive and unequivocal tillite horizon — the Port Askaig Tillite — which must be either Sturtian or Marinoan, the evidence for the other candidate horizon being a tillite is much poorer. The 660Ma date on the Ballachulish Slate is also relevant here, Rooney *et al*. (2011) using it to favour a date for the Port Askaig Tillite of *c.* 650Ma.

Clearly, there is still much to be resolved about the dating of the Dalradian. However, it is increasingly looking as though the bulk of it was deposited during the Neoproterozoic, any Cambrian sediments being thin and condensed, and that sedimentation began, if one includes the Grampian Group, soon after the Knoydartian Orogeny. In round numbers, sedimentation of the Grampian to Southern Highland Groups could have occupied the interval from 800–550Ma.

As a sense check of this time interval, it is interesting to look at deposition rates. It has often been stated that the Dalradian is *c.* 25km thick (Harris *et al*. 1978). This figure is arrived at by adding together the maximum thickness of each formation seen in the whole stratigraphic column. It is likely that the thickness deposited at any one point was less than half of this figure, a thickness that is about the maximum that can be deposited in a sedimentary basin by crustal stretching and/or loading. However, it is a valid figure for calculating an average sedimentation rate

Figure 6 Stromatolitic dolomite from the Bonahaven Dolomite, Bonahaven, Isle of Islay. An example of one of the several limestone or dolomite horizons within the Dalradian from which stable isotope and other chemical data can be derived for use in stratigraphic dating. The field of view is c. *1m across.*

Figure 7 The Port Askaig Tillite, Port Askaig, Isle of Islay. The best developed tillite unit in the Dalradian. The large granite clast shown here is c. *300mm across.*

Geikie's 800 Ma		Macduff Slate Loch na Cille BB	Macduff Slate
Harrison 605 Ma	Loch na Cille BB	Shallochy Corg	Port Askaig Tillite
Shurian 700–720 Ma	Port Askaig Tillite Kinlochleggan BB	Port Askaig Tillite	Kinlochleggan BB

Table 1 Different interpretations of the age of the Dalradian tillites.

for the most actively subsiding parts of the Dalradian basin, which were continually shifting, throughout the whole 250my of Dalradian time: 2km in 250my is 100m/my. Figures in the range of 50–200m/my are typical for predominantly coarse clastic deposition in extension basins and continental margins.

Plate tectonic context

The thickness and extent of the Dalradian and the presence of similar rock units of broadly similar age in Newfoundland, Scandinavia and Greenland shows that it was part of an extensive zone of crustal extension during the late Neoproterozoic. The presence of tidal sandbodies, such as the Appin and Jura Quartzites (*see* Fig. 3), is consistent with this zone forming a gulf between two landmasses rather than lying on a passive continental margin, until after the final continental rupture dated by the Tayvallich Volcanics. Plate reconstructions consistently place the Dalradian Terrane between the Laurentian and Baltic cratons during the late Neoproterozoic, but with what is now northern Norway adjacent to the Dalradian Terrane (e.g. Cawood *et al*. 2010). Both the petrography of the Dalradian (Anderton 1980, Evans *et al.* 1998) and the ages of its detrital zircons (Cawood *et al*. 2003) are consistent with derivation from the sort of Proterozoic and Archaean rocks seen to the north-west in Greenland and Canada. There is no good reason to invoke major displacements between the Dalradian Terrane and these potential source areas.

The Dalradian Terrane was undergoing deformation and metamorphism (the Grampian Orogeny) by the Arenig (Lower Ordovician) owing to the collision of a volcanic arc with this part of the Laurentian margin. As there is no evidence for subduction under the Dalradian at this time, it is thought that the arc advanced towards Laurentia owing to south-east directed subduction under the arc, as proposed by Ryan and Dewey (1991). The deformation would have produced a mountain range that was uplifted and largely eroded during the Ordovician and Silurian. The Baltic plate collided back with Laurentia, causing the Scandian phase of the Caledonian Orogeny, during the Silurian, but this collision took place to the north or north-east of the Dalradian Terrane so had little effect on it. When the East Avalonian plate collided with the more southerly segment of Laurentia during the Silurian, the Dalradian Terrane had already been deformed and uplifted. During the later phases of this collision, which can be referred to the Acadian Orogeny, the Dalradian Terrane was moved some distance north-eastward along the Laurentian margin due to strike-slip faulting.

In summary, the rocks that make up the Dalradian Terrane record a long period of deposition and deformation. The oldest sediments, the clastic sediments of the Grampian Group, may be the molasse of the Knoydartian mountain belt, deposited rapidly in post-orogenic basins. As the source areas were eroded down and the drainage area expanded, the sedimentation rate slowed, as is indicated by the presence of the limestones and black slates of the Appin Group. At this time, gentle extension between the Baltic and Laurentian parts of the supercontinent, known as Rodinia, must have produced a gulf along the zone of weakness formed by previous plate collisions. In Argyll Group times, more pronounced rifting produced more rapid subsidence and following the eruption of the Tayvallich Volcanics, sea-floor spreading drove the Baltic and Laurentian plates apart, leaving the Dalradian Terrane lying on the Laurentian continental margin. The Southern Highland Group records sedimentation on the thinned, outer continental margin during the latest Neoproterozoic. The Trossachs Group may record slow or condensed deposition during the latter part of the Cambrian, a time when the Laurentian continent became increasingly peneplained and arid, with the result that limestones dominated the marginal marine environments seen in the Northwest Highlands.

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Book review

Ragan, Donal M. 2009 *Structural Geology: An Introduction to Geometrical Techniques* (4th edn). Cambridge: Cambridge University Press (ISBN 978-0-521-74583-3 (paperback) and 978-0-521-89758-7 (hardback); 602pp; £40.00 (paperback) and £97.00 (hardback))

If you are an undergraduate geology student you will have become familiar with words such as 'strike', 'dip', 'fault' and 'planes'. You will have read much about them in your textbooks and be confident about applying them in relevant situations. What about their practical implications, however? If you are bit like myself, you might feel uneasy about drawing cross-sections or measuring strike and dip in the field.

This is where *Structural Geology* begins. The author aims to provide the student with a thorough understanding of everyday geological terms, not only theoretically, but also practically. The book is subdivided into chapters on structural planes, faults, stress, folds and topography, maps and cross-sections, to name but a few.

Each chapter begins with a brief introduction to set the scene, plus the definition of relevant terms if they are used in this chapter for the first time. Each chapter then explores basic concepts as well as step-by-step instructions to the methods used. Readers are guided through problems and worked answers so that they can get a really good understanding of the geometrical conditions arising from real-world geological settings. Every now and again, the author gives tips on how to do things in the field, or points to potential pitfalls. He never makes any assumptions about what the reader knows and even explains 'trivia' — such as the concept of significant figures — without ever straying too far from the actual subject matter.

Each chapter concludes with exercises, the answers to which are given on the publisher's website.

Overall, the book is written in an easy-to-read style. The numerous sketches and the uncomplicated approach to the mathematics involved make *Structural Geology* easy to study. It is particularly the way in which maths is embedded within a geological context that makes those of us who tend to try to forget the need for mathematical methods feel that it is actually doable.

Structural Geology is the most fundamental and practical textbook I have come across yet, and while it is aimed at undergraduate students, even more experienced geologists will find it useful as a compendium of the necessary geometrical techniques required in structural geology.

— Marion Seitz

Book review

Yeats, Robert 2012 *Active Faults of the World*. Cambridge: Cambridge University Press (ISBN 978-0-52119-085-5; hardback, xii + 621pp: £50)

This is a most remarkable and authoritative work. Robert Yeats is Emeritus Professor of Geology (Earthquake Geology and Tectonics) at Oregon State University and a senior partner in Earth Consultants International, a geological consulting company that "unites the state-of-the-art knowledge and research talents of academia with the experienced and practical skills of industry". His best-known work is *Living with Earthquakes in California: A Survivor's Guide* [1998 Oregon State University Press (ISBN 978-0870714375)].

Active Faults of the World is the fruit of 30 years international co-operation, begun through UNESCO as a project of the International Geological Correlation Programme. Dr Yeats has been involved in the programme during all those years and this book is sponsored by the Global Earthquake Model five-year initiative (http://www.globalquakemodel.org) launched in 2008. It seeks to meet a perceived need for "an active tectonic geography of the world's active faults", and in my lay view meets this goal superbly.

There is a limpid first chapter on tectonics, structural geology, seismic waves, tectonic geodesy (precise measurements), earthquake geology at mainshock depths, Quaternary dating techniques (because the book has a strong focus on the historical record), tectonic geomorphology, weathering and soils, and palaeoseismology. The author then proceeds methodically around the world from Alaska to Hawaii noting every single active fault.

The 12 pages on New Zealand show his method: first a brief historical introduction, then succinct paragraphs on the Hikurangi subduction zone (east of the North Island), the Taupo volcanic zone in the North Island, the strike-slip faults in the southern North Island, those in Marlborough and Canterbury, the Alpine fault, reverse faults in the South Island, and a summary.

'The lesson of Christchurch' concludes the whole book: "the next big one" "came as a complete surprise, rupturing a right-lateral strike-slip fault that no one knew existed … because it was overlain by a Late Glaciation (16ka) surface covering sediments transported eastwards from the Southern Alps".

Not surprisingly, in view of Christchurch, Port-au-Prince, and the 2011 Japan earthquake and consequent tsunami, the book has an urgency about it. This is not least because "large populations are moving to megacities, with little attention paid to earthquake-resistant construction standards, particularly in the developing world, and some of these overcrowded cities are close to active faults." The author wrote the chapter on the Caribbean plate in 2009 and "identified Port-au-Prince, Haiti, as a potential earthquake time bomb. Shortly afterwards the 12 January 2010 earthquake destroyed that city, and I decided that the book should focus on other earthquake time bombs as well."

With 97 pages of references and 214 maps and figures this is a most well-resourced volume.

— Philip Clark, MA (Oxon), BSc (Hons) Open

The Grampian evolution of the Caledonides of NW Ireland

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Abstract

This paper focuses on the Grampian evolution of components of the north-west Irish Caledonides and their correlatives in Scotland. It considers basement-cover relationships in north-west Ireland, and investigates the timing of peak metamorphism in the Laurentian cover (the Dalradian of Ireland and Scotland) from mineral cooling ages and U-Pb zircon geochronology of syn-orogenic intrusives. It also examins the structural, metamorphic and geochronological constraints across the Highland Boundary Fault and its continuation into Ireland, the Fair Head–Clew Bayline. This includes the Grampian evolution of the Highland Border and Clew Bay complexes, as well as outboard Laurentian microcontinents, such as the Slishwood Division and Tyrone Central Inlier. Lastly, this paper examins timing constraints on the Grampian Orogeny based on the detrital record and volcanic geochemistry of an early Ordovician fore-arc basin, the South Mayo Trough in western Ireland.

Introduction

During the latest Precambrian a wide ocean (termed the Iapetus Ocean) separated the Laurentian continent (Laurentia), which included north-west Ireland and Scotland, from the Avalonian microcontinent (Avalonia), which included south-east Ireland and England. During the Cambrian, this ocean started to close. A series of tectonic events, ranging in time from the Cambrian to the Devonian, were associated with the ocean's closure. Combined, this series of tectonic events has been termed the Caledonian Orogeny (McKerrow *et al.* 2000), although here the term 'Caledonian orogenic cycle' is used instead.

In Ireland and Britain, the Caledonian orogenic cycle comprises two main phases. These are an Early–Middle Ordovician (475–460Ma) phase, termed the Grampian Orogeny, and an Early Devonian (405Ma) phase, termed the Acadian Orogeny. The Grampian Orogeny was caused by the collision of the Laurentian continental margin of north-west Ireland and Scotland with an oceanic arc terrane (Fig. 1A). This arc was intra-oceanic, and was produced by the subduction of oceanic crust within the Iapetus Ocean. Following the collision, subduction of oceanic crust continued. The Laurentian margin of north-west Ireland and Scotland progressively approached the Avalonian microcontinent to the south (Fig. 1B). By the Late Silurian, all the intervening oceanic crust had been subducted, and a continent — continent collision ensued (Fig. 1C). The boundary between Laurentia and Avalonia is termed the Iapetus Suture. The Acadian Orogeny is the final (Early Devonian) stage of this collision.

The Grampian Orogeny

Lambert and McKerrow (1976) recognised that the Dalradian sequences of the Scottish Highlands had undergone polyphase deformation and metamorphism during the Ordovician. This phase of orogenic activity clearly predated the post-Silurian deformation, also called 'Caledonian', seen elsewhere in Britain and Ireland. They coined the term 'Grampian Orogeny' to distinguish the Ordovician tectonic event. The Grampian terrane of

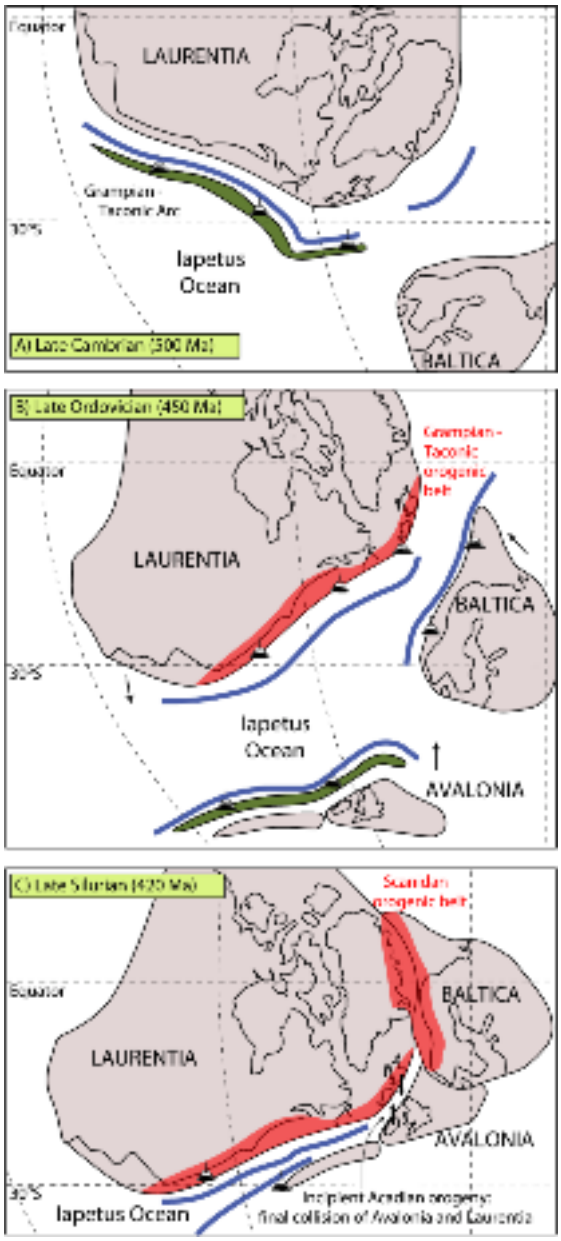

Figure 1 Schematic tectonic evolution of the Caledonian orogenic cycle (the closure of the Iapetus Ocean), showing major orogenic events (e.g. the Grampian and Acadian). Volcanic arcs are shown in green; trenches are shown in blue and indicate the polarity of subduction; collisional orogens are shown in red. (A) South-directed subduction creates a volcanic arc within the Iapetus Ocean outboard of Laurentia; (B) this arc collides with Laurentia causing the Grampian Orogeny, and north-directed subduction under Laurentia begins, contemporaneous with south-directed subduction beneath Avalonia; (C) the Iapetus Ocean has nearly closed. The 'head-on' collision of Baltica and Laurentia causes the Scandian Orogeny, while the highly-oblique collision between Laurentia and Avalonia causes the Acadian Orogeny.

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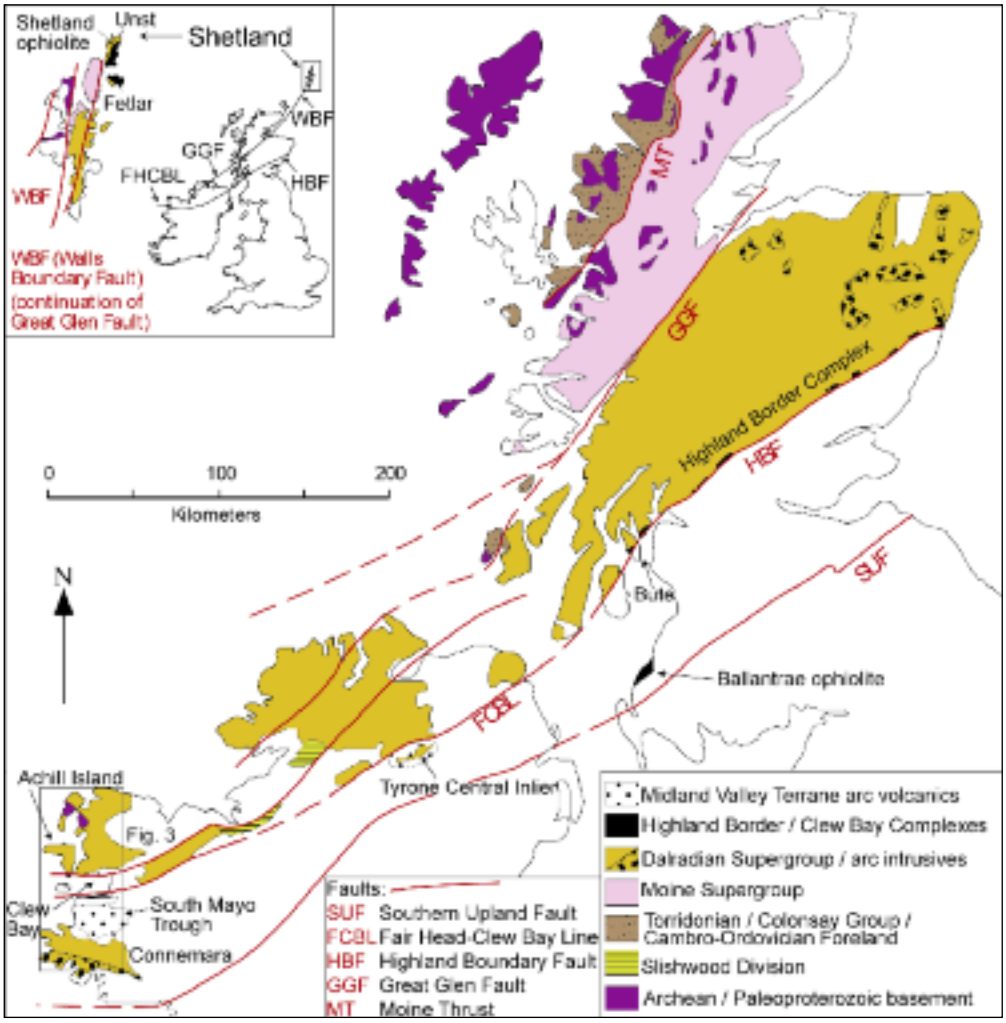


Figure 2 Geological map of the Caledonides of north-west Ireland and Scotland; inset shows a simplified geological map of Shetland and its relationship to the British and Irish Caledonides.

Scotland and north-west Ireland is the type locality for Barrovian (regional) metamorphism that is recognised in most of the major mountain belts of the world. It is thought to have resulted from the collision of the Laurentian margin with an infant oceanic arc and associated suprasubduction ophiolite (e.g. Dewey and Shackleton 1984; Dewey and Mange 1999) during the Early — Middle Ordovician. The Grampian Orogeny is broadly equivalent to the Taconic Orogeny of the Appalachians and eastern maritime Canada.

In Scotland, the suture between the deformed Laurentian margin (Dalradian Supergroup) and the colliding arc (Midland Valley Terrane) is sharply defined by the Highland Boundary Fault (Fig. 2), along which a series of Lower Paleozoic deep marine sedimentary rocks and isolated occurrences of mafic and ultramafic rocks crop out. Termed the Highland Border Complex, this belt has figured prominently in tectonic reconstructions of the Grampian belt (e.g. Dewey and Mange 1999), where it is usually regarded as an accretionary complex. A recent reinterpretation of the Highland Border Complex (Tanner and Sutherland 2007) suggests the majority of the sequence is in stratigraphic continuity with the Dalradian Supergroup, with the exception of a series of poorly exposed fault-bound slivers of ophiolitic rocks within the fault zone, known as the Highland Border Ophiolite (Tanner and Sutherland 2007). Detailed reviews of the Highland Border Ophiolite are given in Tanner (2007) and Henderson *et al.* (2009).

The continuation of the Highland Boundary Fault in Ireland is referred to as the Fair Head — Clew Bay Line (FCBL; *see* Fig. 2), which generally separates the Dalradian Supergroup from the Clew Bay Complex (the Irish correlative of the Highland Border Complex) and an outboard volcanic arc terrane to the south-east. The western Atlantic coast reveals one of the most complete sections through the Grampian orogen, with all of the major components of the orogen well exposed (Fig. 3, *opposite*), including Laurentian cover (the Dalradian Supergroup), accretionary complex (Clew Bay Complex), suprasubduction ophiolite (Deer Park Complex) and arc volcanic rocks and fore-arc basin (Lough Nafooey Arc and South Mayo Trough). The outboard volcanic arc terrane is represented by the Tyrone Igneous Complex in the central part of the north of Ireland. Additionally, unlike the Dalradian of Scotland, the Dalradian rocks of Connemara and the Tyrone Central Inlier (Chew *et al.* 2008) also crop out to the southeast of the FCBL, i.e. outboard of the main belt (*see* Fig. 2).

Grampian evolution of the components of the orogen

This paper summarises the the Grampian Evolution of the Caledonides of north-west Ireland, the most complete section through the Grampian Orogen. It consists of summaries of the geological histories of each of the 'components' of the orogen in turn. It pays particular attention to the timing and pressure-temperature conditions of ophiolite obduction versus the timing and pressure-temperature conditions of deformation in the Dalradian Supergroup (the Grampian Orogeny *sensu stricto*). It concludes with a summary of the evolution of the Grampian Orogenic belt in north-west Ireland.

The Laurentian cover: the Dalradian Supergroup

The Dalradian Supergroup of Scotland and Ireland is a metasedimentary succession that was deposited on the eastern margin of Laurentia during the late Neoproterozoic and Early Cambrian.

Existing constraints imply that the base is younger than 800Ma and that it extends to at least 510Ma (Smith *et al.* 1999; Tanner and Sutherland 2007). It comprises a thick sequence of lithologically diverse metasediments and mafic volcanics. Lithostratigraphic correlation is hampered by the almost complete absence of stratigraphically useful fossils, complex polyphase deformation and rapid lateral facies changes. Despite these difficulties, a coherent lithostratigraphy from western Ireland to the Shetland Islands has been established (Harris *et al.* 1994) comprising four Groups: Grampian, Appin, Argyll and Southern Highland.

The Dalradian outcrop in Scotland and Ireland is one of the classic areas for the study of rocks that have undergone multiple phases of folding (Fig. 4, *overleaf*) and also for those that have undergone regional metamorphism. Barrow (1893), working in the south-east Highlands of Scotland, was the first to show that differing mineral assemblages in pelitic rocks reflect different conditions of metamorphism. It is now recognised that much of the Scottish and Irish Dalradian has experienced what is now termed Barrovian (medium-pressure) regional metamorphism. In the Dalradian rocks of north-west Mayo (*see* Fig. 3), the metamorphic grade is highest closest to the basement core (the Annagh Gneiss Complex), where it locally reaches the sillimanite zone. The peak metamorphic temperatures decrease to the south towards Clew Bay. However, at the southern margin of the Dalradian outcrop, on southern Achill Island adjacent to the Fair Head–Clew Bay Line, blueschist-facies metamorphism occurred (indicative of high pressure, low temperature metamorphism) (Gray and Yardley 1979). The blueschist-facies assemblages (Fig. 5, *overleaf*) developed at P–T conditions of 10.5±1.5 kbar and 460±45 ºC contemporaneously with the Barrovian metamorphic assemblages to the north (Chew *et al.* 2003). Peak metamorphism in the Dalradian of north-west Ireland has been dated at *c*. 460Ma by the Sm–Nd garnet method (Flowerdew *et al.* 2000). ^{40}Ar-^{39}Ar and Rb–Sr ages of metamorphic minerals (principally hornblende, biotite and muscovite) range between 470Ma and 455Ma and are consistent with crystallisation and subsequent cooling during the Grampian Orogeny at *c*. 470Ma (Flowerdew *et al*. 2000; Chew *et a*l. 2010).

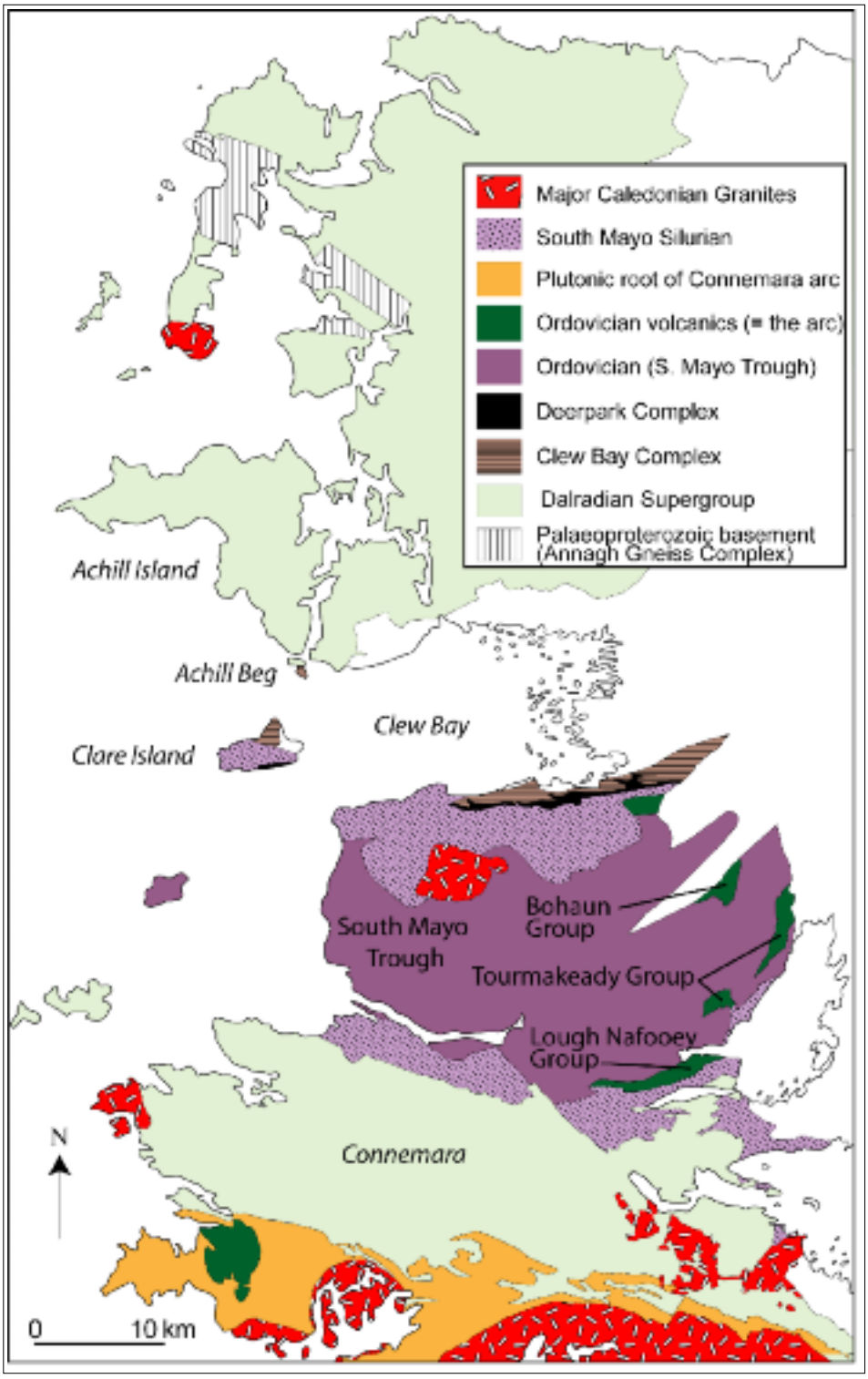


Figure 3 Geological map of western Ireland (counties Mayo and Galway) showing the Precambrian and Lower Palaeozoic rocks discussed in the text.

The accretionary complex: the Clew Bay Complex

The Clew Bay Complex comprises a series of low-grade turbiditic metasediments that have been interpreted as representing an accretionary complex (e.g. Dewey and Mange 1999). On Clare Island, the Clew Bay Complex comprises graphitic mudrocks, spilites, greywackes and micro-conglomerates with clasts of vein quartz, schist, gneiss and granite. The nature of the deformation in these rocks is difficult to ascertain. Chew (2003) concluded that the Dalradian and the Clew Bay Complex on the island of Achill Beg (*see* Fig. 3) share the same polyphase structural history across the Achill Beg Fault. An alternative interpretation of the structure of parts of the Clew Bay Complex is given by Max (1989) who reinterpreted it to be largely tectono-sedimentary in origin (i.e. a chaotic mélange), with blocks of greywacke up to 8m across floating in a black mudstone matrix. A Middle Cambrian–Early Ordovician sponge (*Protospongia hicksi*; Rushton and Phillips 1973) and Early–Middle Ordovician coniform euconodonts (Harper *et al*. 1989) have been obtained from the Clew Bay Complex. Chew *et al*. (2003) estimated metamorphic temperatures of 325–400˚C and pressures of 10kbar for the Clew Bay Complex, which is similar to the high-pressure–low-temperature metamorphic conditions experienced by the blueschist-facies Dalradian rocks to the north, while metamorphic cooling ages from ^{40}Ar–^{39}Ar ages from metamorphic muscovite cluster at *c*. 470Ma (Chew *et al*. 2010).

Figure 4 Polyphase folding in the Dalradian rocks of Connemara.

The ophiolite: the Deerpark Complex

The high-grade Deer Park Complex is in tectonic (faulted) contact with the low-grade Clew Bay Complex. It consists of a mélange of serpentinite, amphibolite and slivers of metasediment (Phillips 1973). The amphibolites within the Deerpark Complex have a Mid Oceanic Ridge Basalt (MORB)-like trace element chemistry, but pronounced Nb anomalies and neodymium isotopic compositions that are consistent with a juvenile subduction-related origin (Chew *et al*. 2010). The amphibolites and serpentinites have been interpreted by Ryan *et al*. (1983) as representing a dismembered ophiolite. Detrital zircon U–Pb data from slivers of metasedimentary rock within the Deerpark Complex ophiolitic mélange suggest these metasediments are identical to the Dalradian Supergroup. They are interpreted as deepwater sediment on the seafloor of the Laurentian continent, which was then caught up by obduction of the ophiolite (Chew *et al*. 2010). The 'cooling' ages of metamorphic minerals in the Deerpark Complex range from *c*. 480Ma (Rb–Sr and ^{40}Ar–^{39}Ar ages from metamorphic muscovite in the metasedimentary slivers) to *c*. 515Ma (a ^{40}Ar–^{39}Ar hornblende age from an amphibolite), which are significantly older than the *c*. 470–455Ma metamorphic mineral ages recorded from the Dalradian and low-grade Clew Bay Complex rocks to the north (Chew *et al*. 2010). The pressure–temperature conditions in the Deerpark Complex are also different to the low-temperature, high-pressure assemblages found in the Dalradian and Clew Bay Complex rocks, yielding estimates of *c*. 580˚C, 3.3kbar (i.e. shallower and hotter).

The ophiolitic affinity of the high-grade metabasites and serpentinites of the Deerpark Complex means that it figures prominently in tectonic models of the Grampian Orogeny (e.g. Dewey and Mange 1999), with the low-grade turbidites of the Clew Bay Complex interpreted as an accretionary complex and the Deerpark Complex representing a supra-subduction ophiolite (e.g. *see* Fig. 7A). The metamorphic pressure-temperature estimates from the Clew Bay Complex and Deerpark Complex are also consistent with this scenario, as the accretionary complex rocks of the Clew Bay Complex would be expected to have experienced high-pressure, low temperature metamorphic conditions in a subduction zone, while the ophiolitic rocks of the Deerpark Complex would have experienced high-temperature, low-pressure metamorphism within the metamorphic sole of the ophiolite.

Figure 5 Lilac-coloured glaucophane amphibole in a garnet-bearing blueschist from the Dalradian of South Achill Island.

The volcanic arc: the Lough Nafooey Arc

During closure of the Iapetus Ocean, subduction of Iapetus oceanic lithosphere resulted in the formation of an Early Ordovician intra-oceanic arc. In western Ireland, the arc volcanics are exposed in a series of small, fault-bounded inliers, which are collectively referred to in this paper as the Lough Nafooey Arc. This arc presumably forms the basement to the Grampian fore-arc basin (the South Mayo Trough), which is described in the next section. The Lough Nafooey arc includes the Late Tremadoc–Early Arenig Lough Nafooey Group (Ryan *et al*. 1980), the Arenig Tourmakeady Group and the Bohaun Group of unknown age (Graham *et al*. 1989) (*see* Fig. 3). As the arc volcanism spans the Grampian arc–continent collision event, the chemistry of the arc volcanics can be used to constrain the onset of collision.

The oldest biostratigraphically dated (pre-collisional) arc volcanics are the Lough Nafooey Group (*see* Fig. 3b). The strongly juvenile chemistry of the tholeiitic basalts at the base of the Lough Nafooey Group (Draut *et al*. 2004) and the lack of continental detritus in the oldest sediments of that group suggest an origin far removed from the Laurentian margin (Ryan *et al*. 1980). Younger volcanic units in the Lough Nafooey Group exhibit a trend toward higher-silica, higher-K compositions (Ryan *et al*. 1980). The Arenig Tourmakeady Volcanic Group (*see* Fig. 3) contains andesitic and rhyolitic tuffs and volcaniclastic sediments (Graham *et al*. 1989). These volcanics have neodymium isotopic compositions which indicate substantial assimilation of old continental material which is likely because of the Laurentian continent approaching the volcanic arc.

The fore-arc basin: the South Mayo Trough

Whole rock geochemistry demonstrates that the lower portions of the northern limb of the South Mayo trough are derived from a source enriched in Mg, Cr and Ni (Fig. 6, *opposite*), indicative of an ultramafic (ophiolitic) source region (Wrafter and Graham 1989). This prominent ultramafic signature decreases up sequence, as does the abundance of detrital chrome spinel. The drop in detrital chrome spinel abundance coincides with a sudden influx of metamorphic detritus (garnet, staurolite, sillimanite and muscovite) (Dewey and Mange 1999). These data suggest the

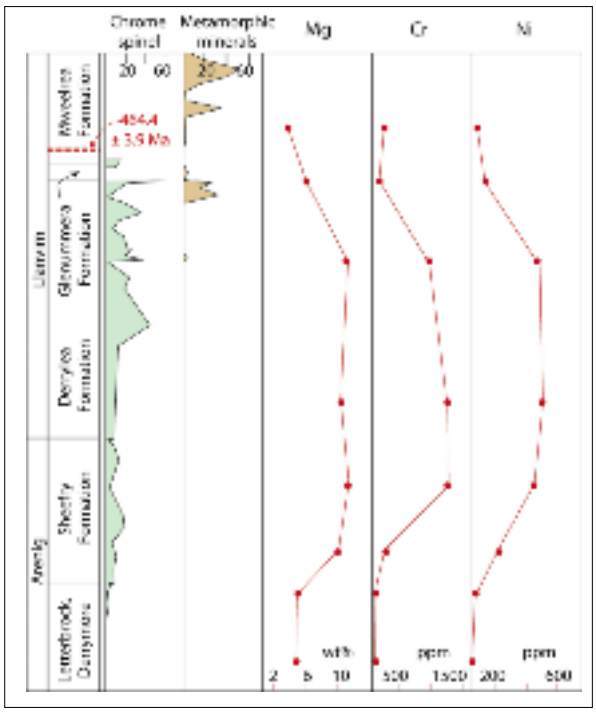


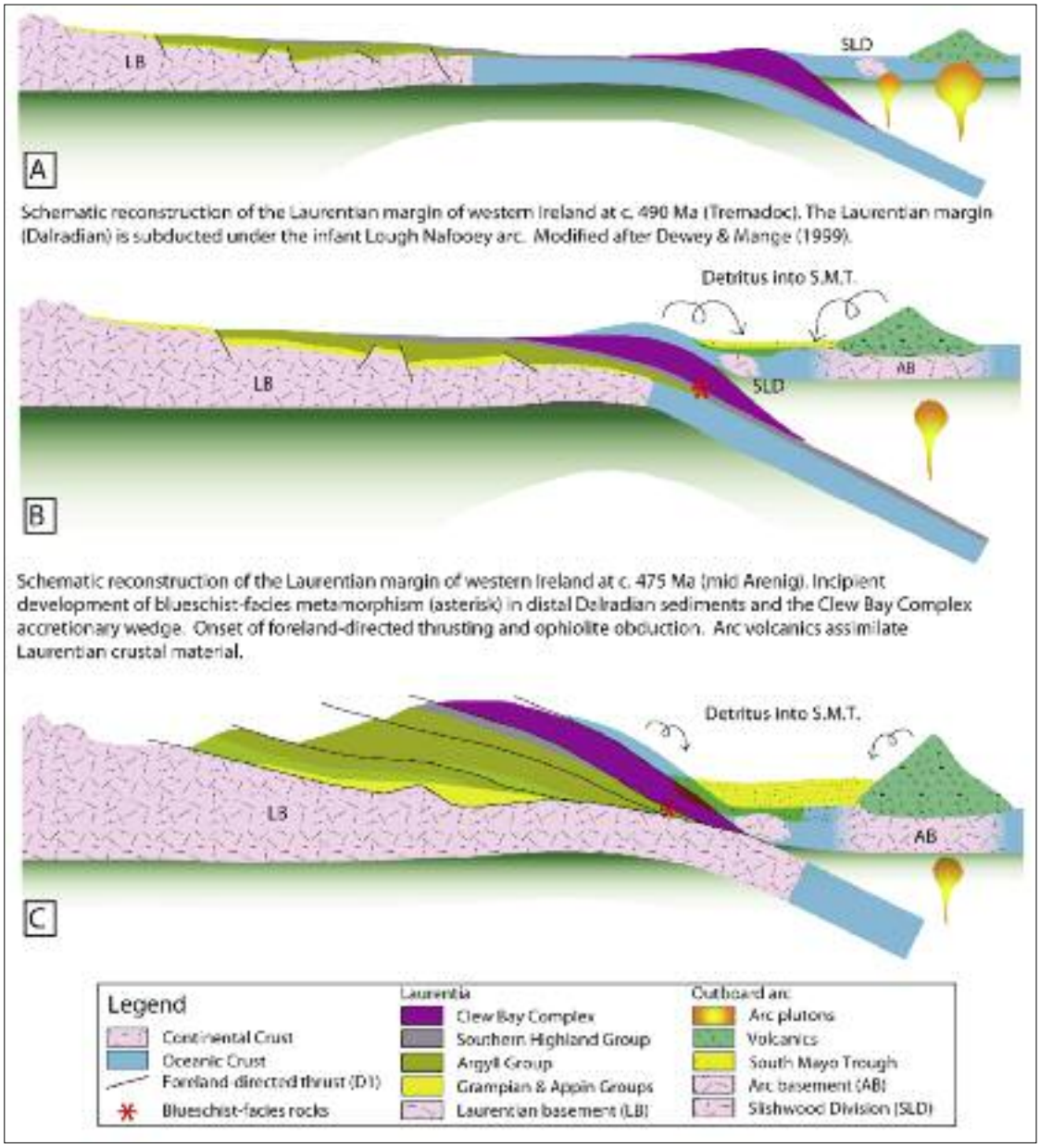
Figure 6 Temporal evolution of detrital heavy mineral assemblages of sandstones from the northern limb of the South Mayo Trough. The percentage of each component (e.g. chrome spinel or metamorphic detritus) is illustrated in the histogram. Also shown are the whole rock geochemistry (Wrafter and Graha, 1989) and a U-Pb zircon age from an ignimbrite (Dewey and Mange 1999).

progressive unroofing of an ophiolite complex in the Arenig followed by the exhumation of the Grampian metamorphic belt during the middle Ordovician (Wrafter and Graham 1989; Dewey and Mange 1999).

Summary of the evolution of the Grampian Orogenic belt in NW Ireland

The development of the Grampian orogen is schematically illustrated in Figure 7. This is based largely on information derived from the coastal section in western Mayo, which is probably the most complete section through the Grampian orogenic belt, as all the major components of the orogen are present: Laurentian basement (Annagh Gneiss Complex), Laurentian cover (Dalradian

Figure 7 Schematic vertical sections showing inferred tectonic development of the Gramp-ian Orogeny in western Ireland, looking east.


LB
SLD
A
Schematic reconstruction of the Laurentian margin of western Ireland at c. 490 Ma (Tremadoc). The Laurentian margin (Dalradian) is subducted under the infant Lough Nafooey arc. Modified after Dewey & Mange (1999).
Detritus into S.M.T.
LB
SLD
AB
B
Schematic reconstruction of the Laurentian margin of western Ireland at c. 475 Ma (mid Arenig). Incipient development of blueschist-facies metamorphism (asterisk) in distal Dalradian sediments and the Clew Bay Complex accretionary wedge. Onset of foreland-directed thrusting and ophiolite obduction. Arc volcanics assimilate Laurentian crustal material.
Detritus into S.M.T.
LB
AB
C
Legend
Continental Crust
Oceanic Crust
Foreland directed thrust (D1)
Blueschist-facies rocks
Laurentia
Clew Bay Complex
Southern Highland Group
Argyll Group
Grampian & Appin Groups
Laurentian basement (LB)
Outboard arc
Arc plutons
Volcanics
South Mayo Trough
Arc basement (AB)
Slishwood Division (SLD)

Supergroup), accretionary complex (Clew Bay Complex), supra-subduction ophiolite (Deerpark Complex) and arc volcanics and fore arc basin (South Mayo).

In the Clew Bay region in western Ireland, high-grade metamorphism in the Deerpark Complex ophiolite was underway by 515Ma (^{40}Ar–^{39}Ar hornblende age from an amphibolite), while geochronological constraints on the Lough Nafooey arc suggest it was active by *c*. 490Ma. These early stages in the development of the Grampian Orogeny are illustrated in Figure 7A.

Shortly afterwards, final obduction of the Deerpark Complex ophiolite occurs (Fig. 7B). The timing of this obduction event is constrained by the presence of Arenig ophiolitic detritus in the South Mayo Trough (*see* Fig. 6) and the *c.* 480Ma metamorphic muscovite ages obtained from the ophiolitic sole. The arc exhibits a change in chemistry at this time, becoming more silica-rich with evidence of assimilation of continental material. This is probably a result of introducing continental material into the source region of melt production beneath the arc by subduction of deepwater Laurentian slope sediment (Draut *et al.* 2004). Although the absolute age of the blueschists in the Dalradian rocks of South Achill Island is still uncertain, the high pressure–low temperature metamorphism may have happened at this time.

Figure 7C is approximately contemporaneous with the metamorphic peak. Although establishing the kinematics of early structures in a polyphase metamorphic belt is difficult, it appears that many of the structures were directed towards the Laurentian landmass. Thrusting in such a direction may also explain the exhumation of the blueschist-facies metamorphic rocks. If the blueschist-facies metamorphism resulted from subduction of distal Laurentian sediment (e.g. Fig. 7B), then a simple and efficient exhumation pathway would be reversal of the subduction path by transferring the high pressure–low temperature rocks to the upper plate. Subsequent collisional thickening and exhumation would then have resulted in large amounts of metamorphic detritus being transported into the South Mayo Trough during the middle Ordovican (*see* Fig. 6).

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Book report

Mitchell, Ian, Cooper, Mark, McKeever, Patrick and McConnell, Brian 2010 *The Classic Geology of the North of Ireland*. Geological Survey of Northern Ireland (ISBN 978-0-85272-672-3; paperback, 96pp; £10.00

This is an updated form of a tour guide prepared jointly by the Geological Survey of Northern Ireland and the Geological Survey of Ireland, in support of a field trip to mark the celebrations of the Geological Society of London's bicentenary in 2007. It is in the form of a six-day excursion, with four, five or six stops each day. But, as the authors say, it can be used in any way a geological tourist wishes and is in this form because the six groups of stops are roughly six distinct areas of this rich northern part of the island of Ireland (whose geology does not conform to modern political boundaries). The areas of the six groups are:

1. County Antrim Coast Road, Glens, and the Giant's Causeway, an area dominated by the great Tertiary basaltic flows, some black outcrops strikingly emplaced on white chalk cliffs, and with other points of interest: the Portrush sill — whose ammonites in hornsfelsed mudstone were a focal point of controversy between Neptunists and Plutonists, the Larne tsunamite, etc.

2. North County Donegal, focussing on late Silurian–Early Devonian granites emplaced in metamorphic rock of the Dalradian supergroup.

3. South County Donegal, focussing on rocks of the Dalradian and the unconformable basal Carboniferous calcareous sandstones with beds of sandy oolite.

4. County Sligo and the Fermanagh-Cavan Marble Arch caves, a comprehensive area of Carboniferous rock.

5. Counties Tyrone, Armagh and Down, whose Fintona Block has from the 1980s revealed much hitherto unsuspected about the Variscan Orogenic Cycle, which has gold mineralisation in the Sperrin Mountains, and whose Tyrone Igneous Complex is part of the Midland Valley Terrane, but whose Ring of Gullion complex is dated 58–57Ma.

6. The Mourne Mountains and Ards Peninsular, with Tertiary granites emplaced into Silurian greywacke and mudstone, and conformable with the Southern Uplands accretionary prism model.

All this is clearly and attractively presented, with 34 colour figures, 60 colour photographs, a short bibliography and a good index. An excellent feature is that "this book blends a factual account of the rocks and landscapes with items of cultural, historical, and social interest." At £10 it is an absolute snip and an essential item of your luggage for that trip to the north of Ireland.

— Philip Clark, MA (Oxon), BSc Hons (Open)

Book review

Dinwiddie, R., Lamb, S., and Reynolds, R. 2011 *Violent Earth*. London: Dorling Kindersley (ISBN 978-1-40539-280-8; hardback, 360pp pages; £25)

Covering volcanoes, earthquakes, hurricanes, mudslides, tsunamis, *et al.*, this volume visually depicts just about every natural phenomenon that shapes our planet.

The book begins with an explanation of Earth's origin and its internal structure, together with plate tectonics and boundaries, before linking this into a chapter on mountain building. Chapter 3, on volcanoes, is the longest. It discusses the various types of volcanoes and eruption styles, and also such features as tuff rings, calderas and fumaroles. Earthquakes are the content of the next chapter, and then we move on to look at various ocean phenomena, including ephemeral islands and tsunamis. As this is not exclusively a geology book, there is also a chapter on extreme weather events, explaining the likes of jet streams, tornados and ice storms. The final chapter is a reference section containing a useful summary of various 'Earth-event' facts and figures. It's not all geology and meteorology though, as the occasional human element is included too.

The book, whose editorial consultant is David Rothery, is up to the usual high standard of the publisher's 'popular science' offerings, and as well as containing much easily understandable text, includes a wealth of photographs with detailed captions, cutaway diagrams, sonar and satellite images, and maps. Several of the photographs can best be described as stunning, particularly those of an approaching pyroclastic flow, a bursting magma bubble and cloud-to-ground lightning.

Within each chapter each item has its own double-page spread, and the book is peppered with brief case studies that help to explain and visualise a particular event. Some of these case studies demonstrate the book's timeliness, as examples include the Eyjafjallajökull eruption of 2010 and the Christchurch earthquake of 2011.

The book has set itself a tough challenge to depict all these natural processes and events in one volume, but it succeeds, albeit rather briefly for each. This leads to perhaps the only problem, if problem it be, that this reviewer has found: because of each item's brevity, you are just 'getting into' an item when it is over. But this is the price to pay for a tome attempting to cover and summarise such a wide variety of phenomena — and it does this very well. Recommended.

— Paul Atkinson, BSc (Hons) (Open)

Book review

Jerram, Dougal 2011 *Introducing Volcanology: A Guide to Hot Rocks*. Edinburgh: Dunedin Press (ISBN: 978-1-90671-622-6; paperback, x+118pp; £9.99)

'Is it worth a tenner?' I wondered. The pictures alone justify the price tag of this easy-to-read book (OU Level 2?).

The reader is first introduced to the world of volcanoes, igneous rocks and minerals, although there are no thin sections. Partial melting and plate tectonics are introduced with clarity. Mantle plumes are mentioned in relation to the Hawaiian hot spot, but a fuller discussion would have been welcome. They are, I think, an explanation for hot spots, not a synonym? A rare lapse, because generally the explanations in this book are accurate and concise. Types and scales of eruption are very well covered, with many tables and figures, condensing a great deal of information into a few pages. The VEI table is helpful for anyone struggling to relate Plinian or Strombolian eruptions to VEI. Lava flows and pyroclastic flows have a good chapter each, summarising much material. Phreatomagmatism possibly deserves a fuller treatment, as does planetary volcanism. The chapter on igneous intrusions takes in the Scottish Igneous Centres, developed in S339. Ophiolites are covered, as are kimberlites and diamonds (I don't remember seeing this in the OU courses).

The final chapters are possibly the most interesting, as they deal with 'hot topics'. The volcanic contribution to climate change and mass extinction occupies a chapter that includes an environmental assessment of the Laki (1783) and Pinatubo (1991) eruptions, and speculation about mega-eruptions and super-volcanoes. VOG (volcanic fog) was a new term to me. Volcano monitoring is well covered and up to date (satellite interferometry); and 3D modelling is considered as an aspiration, perhaps more realistic where internal plumbing is well known. A specimen hazard map and slightly fuller explanation of their importance would have been useful.

'Volcanoes and man' addresses the obvious question, 'Why do people live near volcanoes?', and their effects on human life. The Toba eruption (*c.* 70Ka) and its influence on human evolution is discussed, and the Vesuvius (AD 79) story is told at some length, with pictures of body casts from Pompeii. The book moves up to date with Mount St Helens (1980) and Eyjafjallajökull (2010), including satellite images of the ash cloud from the latter eruption.

The final summary seems brief; the book deserves a chapter pointing forwards and some suggestions for further reading. This is a good book for a tenner, and useful preparation for SXG390.

The author has appeared on television as 'Dr volcano'.

— Peter Blackett, OUGS Northumbria Branch

The Midland Valley of Scotland as a linkage between the metamorphic Highlands and the Southern Uplands*

Brian Bluck

University of Glasgow

Abstract (only)

The Midland Valley of Scotland, interposed between the Highlands to the north and the Southern Uplands to the south, has a crucial role to play in the understanding of the complexities of the growth and evolution of the Caledonides. In 1958 one geologist (Kennedy) saw the region as greatly compressed by over-thrusting from the north-west and south-east However, looking mainly at the Upper Palaeozoic rocks, in 1960 another geologist (George) was more inclined to regard the evidence as an extensional region comparable with the East African rift system.

Sedimentary studies, and examination of the stratigraphy and structure, have both solved and created many problems associated with interpretations of the evolution of the Midland Valley and of the roles of the Highland Boundary and Southern Upland faults.

Lower Palaeozoic rocks are not widely exposed in the Midland Valley, but examination of them has revealed a fascinating history. Ordovician rocks exposed at Girvan comprise a northerly thrust sequence of proximal fore-arc deposits, which then further implies that a volcanic arc existed to the north, within the Midland Valley. Lower Palaeozoic rocks, spread out along the Highland Boundary Fault to the north, suggest that they belong to a complex back-arc basin.

So the Midland Valley at this time was an arc complex.

Silurian rocks are limited to a few small inliers within the southern Midland Valley, along the north-east Highland Boundary Fault and at Portencross. The conglomerates in these southern outcrops, however, have a provenance from the south-east, but do not contain clasts matching the rocks presently exposed in that direction. Early conglomerates comprise igneous rocks, which are replaced upwards by polycyclic metamorphic rocks, and finally by clasts of greywacke. This sequence, coupled with geophysical evidence, suggests that the Midland Valley, with its arc, once continued farther south beneath the present Southern Uplands, which subsequently converged on the Midland Valley block.

Volcanics in the succeeding terrestrial Old Red Sandstone deposits of the central Midland Valley separate the region into two basins. The souhterly region comprises a series of extensional basins, in which accumulated a thickness of conglomerate and sandstone that was intermittently and finally covered with sediment from the north-east.

The northern basins, a thicker and more diverse sequence, have palaeocurrents indicating flow in several directions. Sediments were once again deposited in a series of small basins. An early basin in the Balmaha-Aberfoyle region has southerly derived conglomerates, which extended to the north-north-east, and have been truncated by a splay of the Highland Boundary Fault (the Gualann Fault).

This evidence, together with the physical evidence, implies that the metamorphic rocks of the Southern Highlands have converged on the Midland Valley from the north-west.

* Unfortunately, owing to reasons beyond his control, Prof. Bluck's lecture had to be cancelled.

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Book review

Dosseto, Anthony, Turner, Simon P., and Van Orman, James A. (eds) 2011 *Timescales of Magmatic Processes from Core to Atmosphere*. Oxford: Wiley-Blackwell (ISBN: 978-1-44433-261-2; paperback, 264pp; £39.95)

Magmatic processes are the fundamental ways in which new material is added to continental or oceanic crust. To be able to date the timescales involved is to have essential pieces of information about the nature of the Earth — and indeed, as chapter 1 reminds us, of the Moon. It is only since the 1950s that we have begun to be able to discover these dates through determining accurate isotope ratios of natural rocks. In recent decades geochemical data and detailed geochemical and petrological studies, together with experimental theory modelling, have all made advances. This is particularly true of technological advances in mass spectrometry and the accurate analysis of short-lived radioactive isotopes of the U and Th decay series; and of the realisation that the chemical heterogeneities in crystals can be used to extract time information. "Thus it is now possible to study magmatic processes over timescales ranging from a few minutes to millions of years. This allows us to tackle critical questions about the evolution of Earth Systems: How long is a magma stored in a reservoir prior to eruption? How long does it take to evolve from mafic to felsic magma compositions? How long does it take for a magma generated in the mantle to reach the surface? How long after the Earth was created did a metallic core form?"

A wide range of topics is covered. Chapter 1 uses the extinct ^{182}Hf–^{182}W and ^{146}Sm–^{142}Nd systems to date the differentiation of the Earth. Chapter 2 addresses diffusion-controlled fractionation of trace elements and U-series nuclides during mantle melting processes; results are consistent with physical models of adiabatic compression melting in a mid-ocean ridge setting and of melting due to conductive heating at the base of the lithosphere in an intraplate setting. Heating by a 'mantle plume', they say; but such constructs are much in question today; chapter 3 on melt production in the mantle also seems to assume plumes without caveats. Chapter 5, on melt transport from mantle to crust, also assumes a fundamental difference between MORB (mid-ocean ridge basalts), OIB (ocean island basalts) and IAB (island arc basalts), which Foulger would deny (see review of *Plates vs Plumes*, in *OUGSJ* **32** 1–2, 8). Chapter 6 uses xenoliths to place constraints on rates of magma ascent; chapter 7 chemical equilibration in magmatic crystals to place constraints on timescales of processes. Chapter 8 uses the U-series isotopes to quantify magma cooling and differentiation. Chapter 10 deals with timescales associated with large silicic magma bodies, and shows from the Yellowstone National Park example how difficult it still is to predict how soon the next supereruption will be. The final chapter deals with timescales of magma degassing.

All these and the other chapters need attentive reading, for they are full of equations and other nasties; but the general drift is usually clear. All the chapters have extensive bibliographies and clearly drawn figures, and there are excellent colour plates in the middle of the book.

This is definitely a book to borrow when you next have a sighting of the OUGS library.

[Editor's note: At an OUGSC meeting in 2012 it was decided to disband the OUGS library. Books in it that have been reviewed have been offered to each book's reviewer or to OUGS branch libraries if the reviewer did not want the book. In the future, books sent for review may be kept by the reviewer, who may pass it on to a branch library or to another person if he or she wishes.]

— Philip Clark, MA (Oxon), BSc (Hons) (Open)

Book Review

Jerram, Dougal and Petford, Nick 2011 *The Field Description of Igneous Rocks* (Part of the Geological Field Guide series). Oxford: Wiley–Blackwell (ISBN 978-0-47002-236-8; paperback, 238pp; £22.50)

This book claims to be for "students, professionals and keen amateurs"… "to help understand and interpret better the origins and evolution of complex igneous systems", but does it live up to this claim? It was written to improve and update the original book in the series by Richard Thorpe and Geoff Brown, by including advances in knowledge of igneous geology since the original book was published.

The book is meant to be pocket sized so that it can be taken out into the field; yes, it is a reasonable size and weight to fit a large pocket. For a professional the price is very reasonable but a student could well find it expensive, especially as a non-specialist needs to buy other books in the series; and books used in the field often get damaged rapidly.

The field guide is divided into ten chapters: Introduction and Occurrence; Field Skills and Outcrop Structures; Igneous Textures and Classification; Lava Flows; Pyroclastic Rocks; Shallow Level Intrusions; Granitic Complexes; Mafic Complexes; Magma Mixing and Mingling; and Mineralisation and Geotechnical Properties.

The first two chapters need to be read before going to view rocks in the field, especially the sections on how to record data in a field notebook. These chapters are for beginners.

The book is easy to read and has some great photographs. The diagrams are easy to interpret. Summary tables at the end of 'Field Skills and Outcrop Structures', showing key features to look for, are very useful. 'Igneous Textures and Classification' works step-by-step through colour, texture, fabric and mineral identification, with clear diagrams and a useful table with mineral properties.

All the lava fieldwork described is outside the UK. The examples may be better but some reference to examples in Britain would, I feel, improve the book for student use by British students.

'Mineralisation and Geotechnical Properties' has too many equations. I feel that it is unlikely that OU students will use this information because this work is not really possible for anyone to do outside of a well equipped lab. This chapter must be for professionals, or just for information.

Overall, if you are examining igneous rocks in the field or studying an OU course then, yes, I would recommend this book.

— Wendy Hamilton BA (open), BSc, ex-OU tutor

The demise of the Iapetus Ocean as recorded in the rocks of southern Scotland

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Abstract

The late Neoproterozoic to early Palaeozic Iapetus Ocean attained its maximum size towards the end of the Cambrian Period, separating Laurentia from Baltica to the east and Avalonia to the south. As the ocean began to close, subduction-related volcanic arcs formed at its margins, with vestiges now preserved in the late Cambrian to early Ordovician Ballantrae ophiolite complex. This complex was obducted in the mid-Ordovician as north-directed subduction of Iapetus oceanic crust was established beneath Laurentia. Thereafter, until the mid-Silurian, a supra-subduction accretionary complex built up and now forms the Southern Uplands terrane.

The accretionary complex grew through the southward-propagation of an imbricate thrust system that sequentially stripped the sedimentary cover from the subducting oceanic crust. This has produced a distinctive regional geology of linear, fault-bound tracts within which steeply inclined strata strike north-east–south-west; the oldest tract (Caradoc) forms the north-west margin of the terrane while the youngest (Wenlock) forms the south-east margin. Conversely, each individual tract youngs to the north-west with a thin, basal development of graptolitic mudstone at its south-east margin, conformably succeeded by a much thicker succession of turbiditic sandstone.

As each tract was accreted its strata suffered deformation that was hence diachronous, earlier in the north than in the south. Eventually, in the mid-Silurian, the Iapetus Ocean closed and the accretionary complex overrode and depressed the margin of Avalonia, causing an abrupt increase there in Ludlow sedimentation rates. Deformation of the resulting strata did not come until the early Devonian, c. *400Ma Acadian Orogeny, an event unrelated to the closing of Iapetus. The principal Acadian influence on the Southern Uplands terrane was sinistral transpression, with pre-existing structures re-activated and intensified, and granitic plutons and dyke swarms intruded.*

Introduction

This brief account describes the Early Palaeozoic events that shaped the geology of southern Scotland. It is based on the newly prepared and currently, 4th edition of the British Geological Survey's South of Scotland volume in the British Regional Geology series (Stone *et al.* 2012). This volume provides a comprehensive overview of southern Scotland's geology and is previewed here by permission of the Executive Director, British Geological Survey, NERC.

The Early Palaeozoic Iapetus Ocean

Scotland's border with England coincides, more or less, with one of the most fundamental geological boundaries in Britain. This is the Iapetus Suture (Fig. 1), the trace of a long-vanished, Early Palaeozoic ocean obliterated by the convergence and ultimate collision of the ancient continents that it once separated. The Iapetus Ocean* was initiated during late Neoproterozoic times and had grown to its maximum width by the end of the Cambrian Period. Thereafter, subduction at its margins wrought its eventual

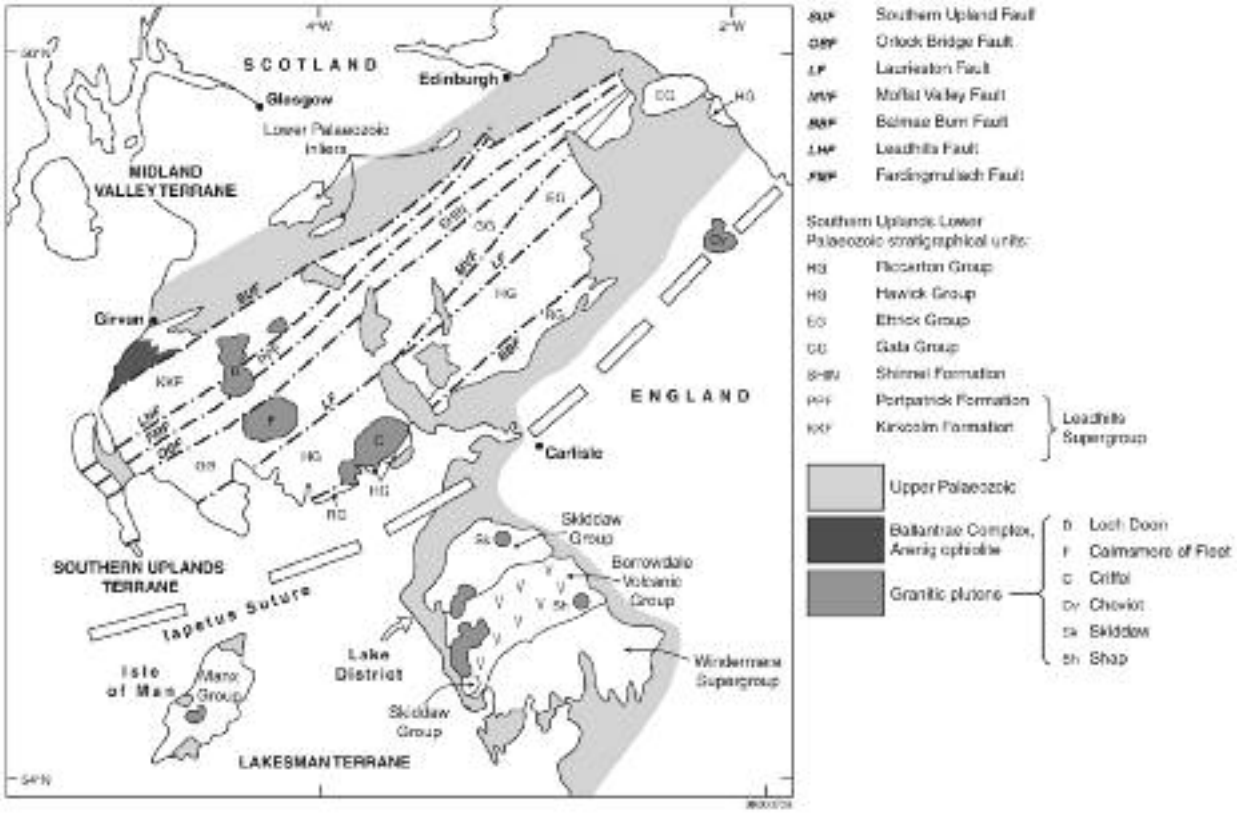

Figure 1 Outline geology of the Iapetus Suture zone, with the Southern Uplands terrane to the north and the Lake District terrane to the south.

OUGS Journal 33 (1) 2012, 29–36

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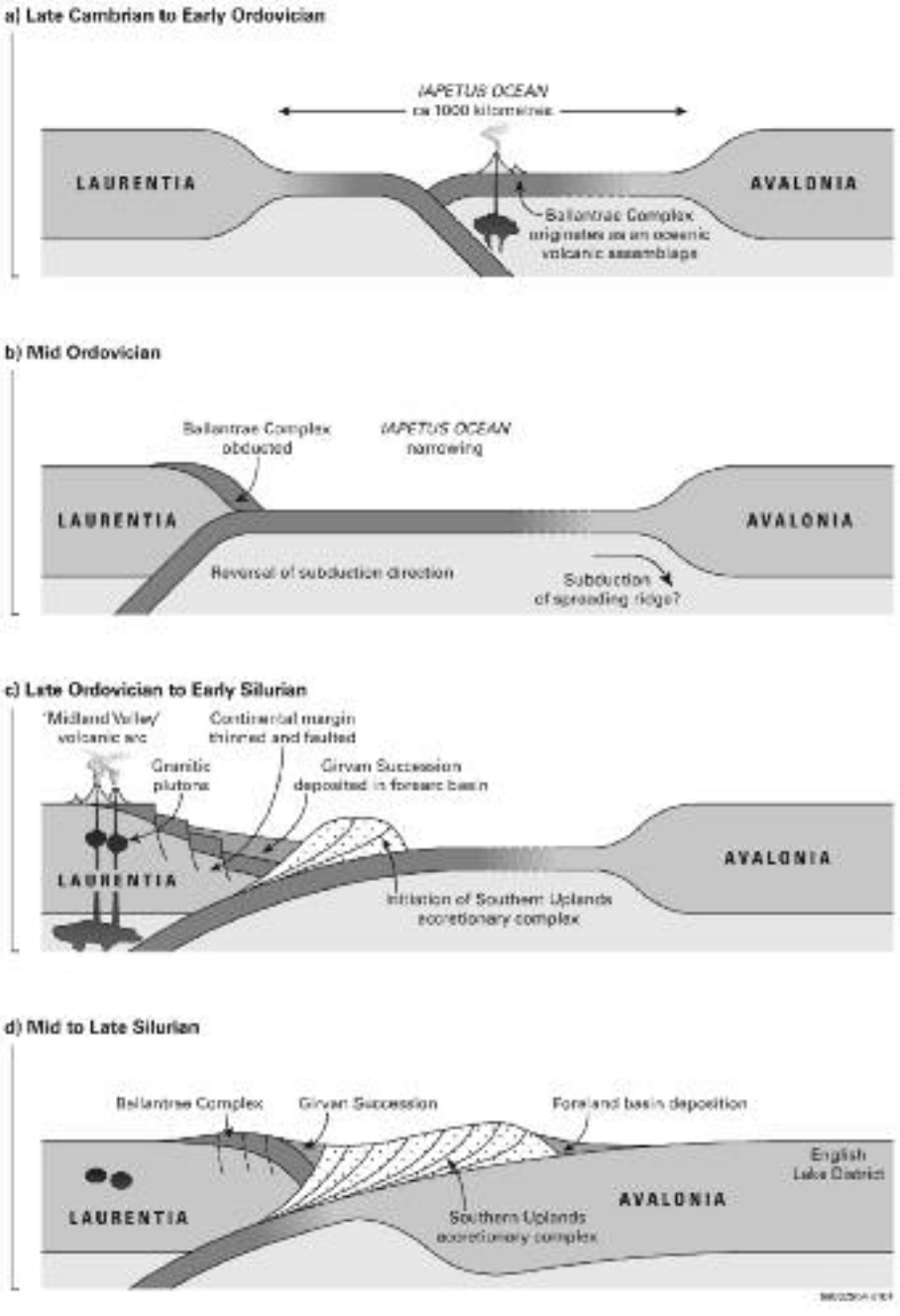
*As a precursor to the Atlantic Ocean it was named after the father of the eponymous Atlas.

destruction and drove the series of collisional events that built up the Caledonian Orogen, a major tectonic zone that can be traced from Scandinavia, through Britain and Ireland, and to Greenland and maritime North America. There are particularly clear geological links from southern Scotland, through Ireland, into Newfoundland, Canada (e.g. Colman-Sadd *et al.* 1992).

Along the northern margin of the Iapetus Ocean at the beginning of Ordovician time, the continent of Laurentia lay in subtropical latitudes. The Archaean and Proterozoic crystalline basement rocks of Scotland formed a part of this continent, and subduction of Iapetus oceanic crust beneath its margin led to the sequential accretion of oceanic rock complexes, both volcanic and sedimentary. These now underlie much of southern Scotland. Forming the southern margin of the Iapetus Ocean during Ordovician time, in southern temperate latitudes, lay the northern part of the Gondwanan continent, from which a fragment had broken away early in Palaeozoic times. This continental fragment, Avalonia, drifted north towards Laurentia as the intervening Iapetus Ocean closed; the principal stages in the destruction of the ocean are illustrated in the series of cross-sectional sketches shown in Figure 2.

One result of the narrowing of the Iapetus Ocean was the convergence through time of the faunal assemblages from the opposing continental margins. The Laurentian and Avalonian shelly fossils such as trilobites and brachiopods, which lived in shallow, coastal marine environments, are quite different in the Ordovician so that distinct 'faunal provinces' can be identified, but the fauna then became progressively more cosmopolitan through the Silurian (e.g. Cocks and Fortey 1982).

Figure 2 Stages in the closure of the Iapetus Ocean, illustrating the formation and obduction of the Ballantrae Complex: a) and b) late Cambrian to mid Ordovician, the depositional environment of the Girvan succession and growth of the Southern Uplands accretionary complex; c) late Ordovician to early Silurian, and the migration of the accretionary complex onto the Avalonian continental margin; d) mid- to late Silurian.



While distinctive shelly faunas characterise the opposing continental margins, graptolites populated the deeper parts of the ocean. This long-extinct group of colonial animals formed the greater part of the oceanic plankton during Ordovician and Silurian times, and their fossils are of great biostratigraphical importance. They establish age and order in the Ballantrae Complex and its overlying sedimentary cover (the Girvan succession), and are crucial to an understanding of the Southern Uplands. Graptolites are commonly slender and delicate and a few centimeters in length, although the length may range from almost microscopic to a metre or so in extreme cases. During the Early Palaeozoic they evolved an extraordinary variety of shapes (Fig. 3, *opposite*), and it is this variety that is key to the biostratigraphical zonation now based on their remains.

Island arcs and obduction

At its northern, Laurentian margin, the first stage in the closure of the Iapetus Ocean was the early Ordovician development of oceanic subduction zones and volcanic island arcs (Fig. 2a), one of which contributed to the Ballantrae Complex of south-west Scotland along with volcanic rocks of within-plate character (e.g. Stone and Smellie 1988). This Tremadoc to Arenig assemblage of oceanic, mostly igneous rocks collided with and was tectonically emplaced (obducted) onto the Laurentian continental margin at *c.* 470Ma (Fig. 2b) to form an ophiolite complex. Its obduction played a peripheral part in the large-scale collision of a volcanic arc complex (now forming the buried core of the Midland Valley terrane) with Laurentia that instigated the Grampian event of the polyphase Caledonian Orogeny.

Within the Ballantrae Complex there is a bewildering array of rock types: ultramafic rock of mantle origin, oceanic lavas erupted in contrasting island arc and within-plate settings,

Figure 3 Graptolites: the biostratigraphical facilitators of geological interpretation in the Southern Uplands of Scotland. Shown are Silurian (Llandovery) examples from the Birkhill Shales Formation of the Moffat Shale Group: (a) Rastrites *sp.; (b)* Campograptus communis rostratus *(Elles and Wood); (c) a climacograptid. This fossil assemblage indicates a level within the gregarius-convolutus biozones (*see *Fig. 4) (BGS image P772042, © NERC, all rights reserved).*

intrusive gabbros and pelagic sedimentary strata (e.g. Thirlwall and Bluck 1984; Smellie and Stone 2001). All were tectonically juxtaposed and obducted as the Iapetus Ocean began to close. By early Llanvirn times the complex was in place and had been deeply eroded. Obduction had been accompanied by a switch in the polarity of subduction and as oceanic crust began to be consumed beneath the continental margin a volcanic arc was generated on what is now the basement to the Midland Valley of Scotland. Relative uplift caused by this 'Midland Valley' magmatism was accompanied by extension and relative subsidence of the continental margin to the south (Fig. 2c). There, the Ballantrae Complex was progressively buried by a sedimentary cover sequence of shallow to deep marine strata that systematically overstepped northward from the late Llanvirn to the early Wenlock (*c.* 460–428Ma). This now forms the Girvan succession. Its northward transgression was controlled by major faults, with downthrow to the south, stepping back sequentially into the Midland Valley arc zone (e.g. Ince 1984). The eventual, probably late Silurian deformation of the Girvan succession, involved the reactivation of those originally normal faults as northward-directed thrust planes (Williams 1962).

Subduction and accretion

While the Ballantrae Complex was being buried beneath the thick Ordovician to Silurian, Girvan sedimentary succession, a very different process was operating farther south. As the Iapetus oceanic crust was subducted beneath the margin of Laurentia, sections of the oceanic sequence and its sedimentary cover were intermittently stripped from the subducting plate and thrust beneath a stack of similar stripped-off slices to initiate an accretionary complex (Fig. 2c). The Southern Uplands terrane represents the deeply eroded remains of this accretionary complex (Leggett *et al.* 1979), which developed along the northern fringe of the Iapetus Ocean sequentially from late Llanvirn to mid-Wenlock times (*c.* 465Ma to 425Ma). Its outcrop extends across southern Scotland and continues south-westward to underlie a broad swathe of country from County Down in Northern Ireland to County Longford in the Irish Republic.

The sedimentary units incorporated into the accretionary complex (Fig. 4, *overleaf*) originated as sand and mud carried by turbidity currents from the continental shelf, through submarine canyons, and built up into huge depositional fans (now the Southern Uplands sandstone formations as summarised by Floyd 2001). The clastic, turbidite deposits filled the supra-subduction-zone trench and encroached onto the oceanic plate, where they covered the sequence of hemipelagic mud (Moffat Shale Group), radiolarian chert and pillow lava (Crawford Group). As the submarine fans built out they overstepped progressively younger oceanic sequences that were continually approaching the continental margin as the oceanic plate was subducted. Then, during the subduction process, discrete sections of the oceanic sequence and its cover of turbidite sandstone were sequentially stripped from the subducting oceanic plate and thrust beneath the stack of similar stripped-off slices that made up the growing accretionary complex. These slices, structurally rotated towards the vertical (and in places even beyond it so that the component beds are inverted), now give rise to the characteristic Southern Uplands lithostratigraphic outcrop pattern of upright beds (Fig. 5, *page 33*) contained in elongated and north-east–south-west-trending, fault-bounded tracts, which are defined stratigraphically in terms of groups and formations (*see* Fig. 1).

The sequential incorporation of structural tracts by accretionary underthrusting also explains the long-standing enigma of Southern Uplands stratigraphy: sedimentary structures such as graded bedding and sole marks show that the upright beds in each tract generally become younger towards the north-west (Fig. 6, *page 33*), whereas graptolite biostratigraphy shows that the oldest tracts form the north-west of the terrane with the youngest tracts at its south-east margin (*see* Fig. 4). Note that in any single tract, the thin (<30m) layer of pelagic mudstone at the base (Moffat Shale Group) was deposited over a considerable period of time, but is overlain by a vastly thicker (up to *c.* 1000m) turbidite sandstone succession that accumulated during the elapse of a single graptolite biozone.

The composition of the turbidite sandstones varies with age, with particularly marked contrasts between some of the Ordovician tracts. Some of the Ordovician sandstones therein are quartzo-feldspathic, whereas others are rich in volcanic detritus, the variation reflecting the different sources from which the original sediment was eroded. The fundamental influence of the compositional range, the detail of which is commonly cryptic, is well illustrated by the British Geological Survey's geochemical atlas (1993) based on analyses of stream sediment across the Southern Uplands region. Two examples are shown in Figures 7 and 8 *(page 34)*, the linear distribution of high and low values running parallel to the geological tract structure and demonstrating a close (but not linear) association between the compositions of the bedrock and the modern alluvial sediment eroded from it (e.g. Stone *et al.* 2003). In Figure 7, a zone of high chromium (Cr) values spatially corresponds to the older tracts of the Gala Group the sandstones of which contain much chrome spinel as accessory grains. Also note the high level of Cr associated with the mafic-ultramafic Ballantrae Complex. In Figure 8, strontium (Sr) is markedly partitioned, with high values over the Leadhills Supergroup and Gala Group contrasting with low values over the Ettrick and Hawick groups. One possible explanation may lie in

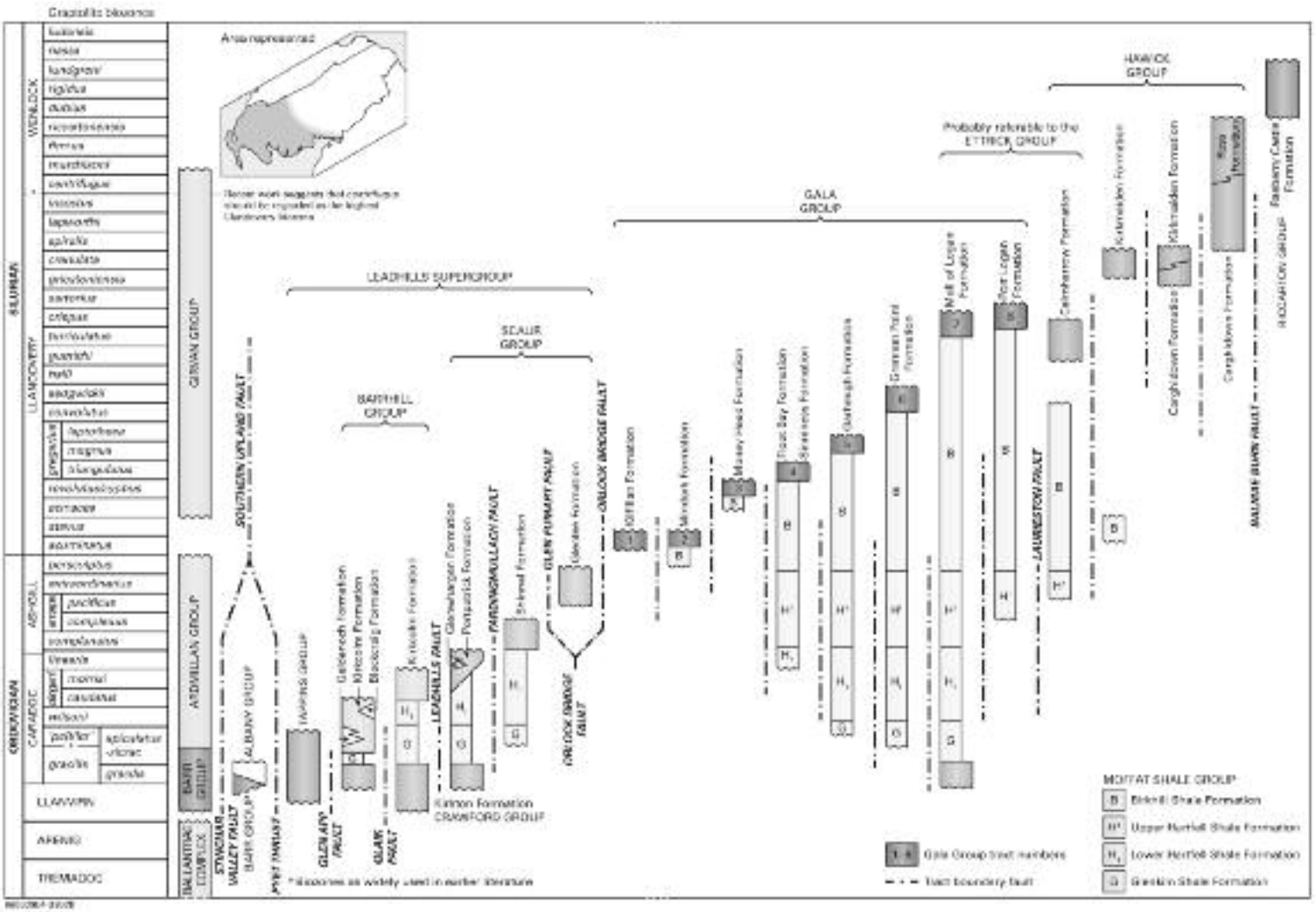


Figure 4 A composite time-stratigraphy profile for the south-west part of the Southern Uplands, illustrating the tract relationships.

the composition of detrital feldspars eroded from bedrock into the stream sediment: more plagioclase in the older rocks to the north, more K-feldspar in the younger rocks to the south. For reassurance that the regional geochemical patterns accurately reflect the underlying geology, despite the anticipated smearing effects of glaciation, note the correlations across the outcrops of the Galloway granite plutons; even the details of compositional zoning are reflected in the stream sediments.

A model of the Southern Uplands as a fore-arc, supra-subduction-zone accretionary complex is now generally accepted, following much discussion of possible alternatives that arose, in part, from the provenance contrasts evident between different sandstone tracts. In particular, sedimentary palaeocurrent indicators (*see* Fig. 6) show that introduction of the volcanic detritus was apparently from the south, i.e. from the oceanic plate rather than the continental margin, a circumstance that has been cited in support of a back-arc origin for all or some of the terrane (Morris 1987; Stone *et al.* 1987). There has also been some discussion of the possible extension of the Girvan depositional setting, an extending and subsiding continental margin, into the northern part of the Southern Uplands terrane (Armstrong and Owen 2001). Analyses of basin thermal history have now ruled out the back-arc possibility (Stone and Merriman 2004), while dating of detrital zircon grains has shown the volcanic detritus to be mostly Neoproterozoic and so unrelated to volcanism contemporary with the depositional setting of the host sandstone (Phillips *et al.* 2003).

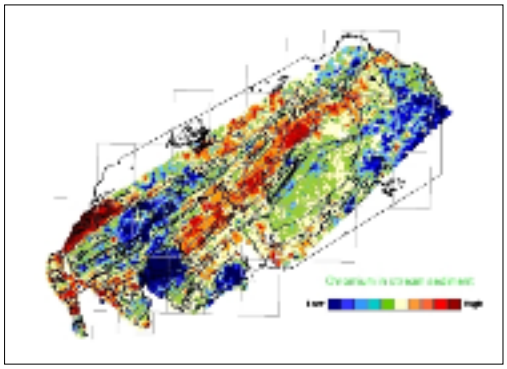
Polyphase folding was imposed on the strata as the accretionary complex built up (e.g. Barnes *et al.* 1989). Early folds were formed in association with thrusting during the subduction process and so of course the earliest deformation was diachronous, older in the north than in the south. Subsequent folds developed as accommodation structures when the early-formed part of the accretionary complex adjusted to continued subduction at its leading edge and responded to intervals of strike-slip movement rather than orthogonal compression. There is however one important difference between the early and late stages in the development of the accretionary complex. The older tracts were accreted from subducting oceanic crust, but by mid-Wenlock times the Iapetus Ocean had effectively closed and the complex, at the leading edge of Laurentia, overrode the margin of Avalonia (*see* Fig. 2d). The meeting of the two continental masses did not produce a deformational climax and instead the accretionary complex continued to advance through the foreland basin that formed ahead of it, above Avalonian continental crust depressed by the encroaching mass of Laurentia. In somewhat pedantic terms, the accretionary complex had become a foreland fold and thrust belt. Thereafter, convergence of the two continental plates probably ceased in Ludlow times, to be replaced by intermittent lateral movement between them.

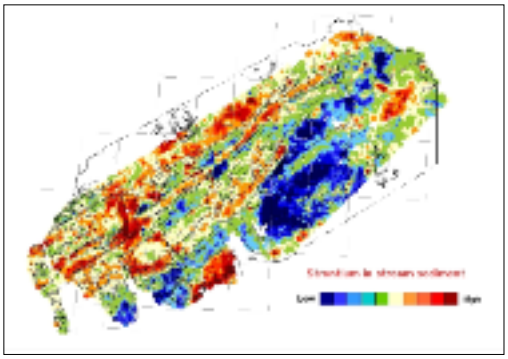
Figure 5 (left) Steeply inclined (slightly overturned) turbidite strata of the Ordovician Kirkcolm Formation, as exposed on the west coast of the Rhins of Galloway at Salt Pans Bay (NW 962 620) (BGS image P008483, © NERC, all rights reserved); (right) Steeply inclined, thinly bedded turbidite strata of the Cargidown Formation (Hawick Group) exposed at Brighouse Bay (NX 632 453) to the south of Borgue (BGS image P220426, © NERC, all rights reserved). Note the well-developed cleavage.

The Iapatus Suture

By late Silurian times the Iapetus Ocean had all but disappeared (*see* Fig. 2c), although the ultimate continental collision was something of a tectonic anticlimax. It was not a mountain-building event of orogenic proportions, and the results are hard to identify in the tectonic record preserved on either the Laurentian or Avalonian margins. The metamorphic grade of the Southern Uplands strata is invariably low, with some rocks only showing diagenetic effects. Instead, there was something of a tectonic continuum, as the Southern Uplands accretionary thrust terrane overrode Avalonia and continued southward as a foreland fold and thrust belt (*see* Fig. 2d). Initially, a load-induced, flexural foreland basin advanced ahead of the thrust front and was an influential control on sedimentation during the accumulation of the mid- to late Silurian parts of the Windermere Supergroup in the south of the English Lake District (Kneller *et al.* 1993). This situation did not last, and by the end of Ludlow times convergence between Laurentia and Avalonia had ceased, the foreland basin failed to migrate farther southward, and isostatic adjustments reversed the earlier effects of loading.

Figure 6 Flute casts, two examples from the Ordovician Kirkcolm Formation showing different styles and current directions: (left) Finnarts Bay (NX 053 722) (BGS image P008425, © NERC, all rights reserved); (right) Portobello (NW 960 665) (BGS image P008463, © NERC, all rights reserved). The shape of the linear flute casts from Finarts Bay indicates current flow from top right to bottom left; the linguiform flute casts from Portobello indicate current flow from top left to bottom right. In both cases the steeply inclined beds are slightly overturned and are viewed looking north.





Figures 7 and 8 Regional geochemical maps for chromium and strontium; for explanation of underlying geological linework see BGS 1:625k Bedrock Geology Map for UK North. *Summary statistics for Cr and Sr are shown in the table below, with analytical values in parts per million (ppm):*

percentile	**95**	**75**	**50 (median)**	**25**	**5**
Cr ppm	*380*	*210*	*150*	*110*	*50*
Sr ppm	*270*	*160*	*120*	*90*	*60*

The tectonic effects seen within the exposed rock sequence, although created by collision-related processes, give little indication of the deeper structure of the suture zone. This is more usefully modelled from geophysical data. A number of seismic lines have traversed the Iapetus Suture Zone and have generally been interpreted in terms of a north-west-dipping, reflective zone projecting to the surface close to the northern coast of the Isle of Man and thence striking north-east beneath northern England. When the seismic results are integrated with regional interpretations of gravity and magnetic data a rather more complicated picture emerges (Fig. 9, *opposite*), in which Avalonian-type crust is caught up in a compound suture zone that extends well to the north beneath the Southern Uplands terrane (Kimbell and Stone 1995).

It is something of a geological paradox that the Lower Palaeozoic rocks of the Laurentian margin did not experience substantial deformation as a result of the collision with Avalonia. One possible effect is seen in the Girvan district, where the normal faults that had controlled deposition of the Ordovician to Silurian fore-arc basin succession were reactivated as north-directed thrusts late in the Silurian. Another possible tectonic outcome of the collision is implicit in Figure 8, wherein Laurentian-type crystalline basement extends from the Midland Valley terrane beneath the northern part of the Southern Uplands. Perhaps large-scale northward thrusting of the accretionary complex onto the Laurentian margin accompanied the demonstrable north-directed thrusting of the Girvan succession (Bluck 1984). The considerable horizontal shortening of the accretionary complex that would have been likely in such circumstances could have been accommodated by the widespread rotation of bedding to the vertical, an attitude hard to attain only by accretionary activity.

Despite the uncertainties, it is clear that the continental collision between Laurentia and Avalonia was not an orthogonal event. A wealth of evidence shows that a sinistral stress regime was important during the later stages of convergence, and indeed may have been the dominant final effect. With a sinistral shear sense applied to the major north-east-trending strike faults, a conjugate pattern of smaller, cross-cutting, late Caledonian strike-slip faults was established across both the Southern Uplands terrane and the Lower Palaeozoic outcrop in northern England. The conjugate fault system comprises strike-slip faults trending either generally north-west with a dextral sense of displacement, or generally east–north-east with sinistral displacement. Although individually minor, these faults were to have a profound structural influence during subsequent episodes of extensional tectonics when their re-activation controlled late Palaeozoic basin development and geometry. More immediately, in the transtensional tectonic regime pertaining during latest Silurian to early Devonian times, strike-slip basins opened across the region and were filled with the clastic, terrestrial sediments of the Old Red Sandstone lithofacies. The transtensional regime might also have been an important factor in the intrusion of the early Devonian granite plutons.

After Iapetus

In the aftermath of the final closure of the Iapetus Ocean a range of igneous rocks were intruded into the Ordovician and Silurian strata of the accretionary complex: a regional swarm of late Caledonian (Silurian–Devonian) calc-alkaline felsic and lamprophyre dykes; several large, early Devonian granitic plutons (*see* Fig. 1); and a number of smaller diorite-granodiorite-granite intrusions. Radiometric dating has confirmed that the first to be intruded were microdiorite and lamprophyre dykes, with ages ranging from 418±10Ma to 400±9Ma (Rock *et al.* 1986). The age of the larger, granitic intrusions varies across the Southern Uplands (Thirlwall 1988), with the northern plutons, such as Loch Doon, giving ages of *c.* 410Ma (earliest Devonian) and proving to be older than the southern plutons that were intruded closer to the Iapetus Suture, such as Cairnsmore of Fleet and Criffel, which give ages of *c.* 397Ma (early to middle Devonian). The southern plutons were coeval with the Skiddaw and Shap granites, intruded to the south of the suture (*see* Fig. 1).

Broadly coincident with the magmatism in southern Scotland and northern England, dated *c.* 400Ma, but focussed farther to the south, was a major deformation event caused by the collision of another Gondwanan continental microplate (Armorica?) at the southern margin of Avalonia. This is commonly described as the Acadian event of the polyphase Caledonian Orogeny, but since it has no connection with closure of the Iapetus Ocean it has also been thought of as a separate orogeny in its own right.

In northern Britain the most widespread Acadian effects seen are the folding and cleavage developed in the Lower Palaeozoic rocks of the English Lake District. In the Southern Uplands of Scotland the Acadian, sinistral-strike-slip tectonic regime reactivated some of the dominant north-east–south-west Caledonian faults, with a particularly intense effect seen along the boundary between the Leadhills Supergroup and the Gala Group (*see* Fig. 1), a boundary marked by the Moniaive Shear Zone (Phillips *et al.* 1995). This tectonic feature interacts with the

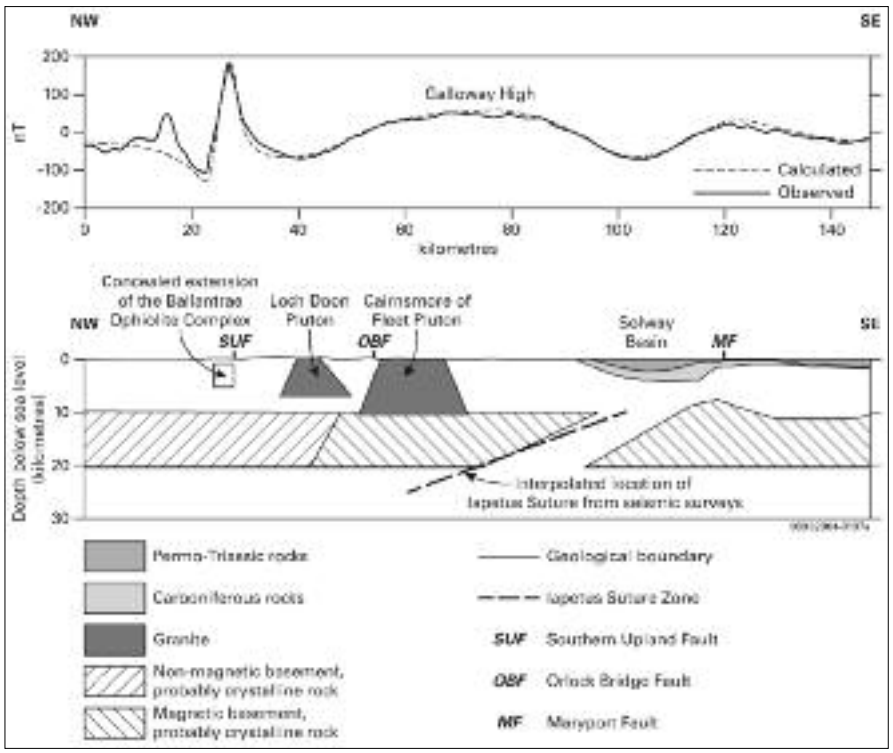


Figure 9 A deep crustal section across the Iapetus Suture Zone based on geophysical evidence and illustrating the long-wavelength magnetic anomaly known as the 'Galloway High'.

thermal aureole around the Cairnsmore of Fleet granitic pluton (*see* Fig. 1) with early-formed metamorphic cordierite porphyroblasts wrapped by the tectonic fabric, whereas late-formed biotites cross-cut the fabric. The U-Pb radiometric age of the pluton is *c.* 397Ma, coincident with the age range established for the Acadian Orogeny farther south in Wales and northern England (e.g. Merriman *et al.* 1995).

Elsewhere in southern Scotland, the Lower Devonian strata were tilted and disturbed during the Acadian Orogeny so that when alluvial basins were re-established, the Upper Devonian strata deposited therein were laid down unconformably on their predecessors, both Lower Palaeozoic and Lower Devonian. Most of the Upper Devonian deposits, red sandstone and siltstone with some conglomerate, were fluvial in origin, although some also show an aeolian influence. By this time, southern Scotland formed an inland part of Laurussia, a 'supercontinent' formed by the amalgamation of Laurentia, Avalonia, Baltica and terranes of Asiatic Russia.

The Iapetus Ocean was ancient history.

Acknowledgements

The ideas explored within this paper owe much to the insights of many colleagues, as discussed with and demonstrated to the author over a number of years. Particular thanks are due to Dr D. J. Fettes and to Dr S. D. Campbell for their astute and helpful reviews, to C. Woodward for assistance with the production of figures, and to N. Breward for the processing of the regional geochemical data. Publication is by permission of the Executive Director, British Geological Survey (NERC).

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Late Caledonian (Scandian) and Proto-Variscan (Acadian) orogenic events in Scotland

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Abstract

The later tectonic phases of the Caledonian Orogeny reflect the collision of Baltica and Laurentia. The result was the Scandian Event in Silurian times, and the oblique docking of eastern Avalonia with Scotland, generating deformation and metamorphism in the Southern Uplands. The exhumation of the Caledonide Oregen was then accompanied by sinistral transtensional faulting and emplacement of granitoid plutons. The Iapetus Ocean was finally closed, and subductiion activity had migrated south to the Rheic Ocean by early Devonian times.

Continental rifting and deposition of the Lower Old Red Sandstone fluvial-lacustrine succession, accompanied by basaltic-andesitic volcanism, occurred across Scotland. Deposition commenced in the late Silurian and continued through to Emsian times, when it was interrupted by the short-lived, northward-directed Acadian Event. The resultant deformation and folding, a product of sinistral transpression, were focused along the major pre-existing faults and shear zones.

Evidence for transpressional movements along the Great Glen Fault (GGF) is found near Rosemarkie, where Moine psammites and semipelites are interleaved with Lewisianoid gneisses in a structural inlier. These lithologies are introduced by pink leucogranite veins that themselves show evidence of two phases of ductile deformation and folding. U-Pb monazite and zircon ages show that the leucogranites were emplaced at c. *399Ma. Leucogranite intrusion and subsequent deformation are interpreted to have occurred during oblique extrusion of the inlier as an elongate 'pip', generated at a north-westward step-over that developed on the GGF during the Acadian event. Crude strain estimates from the inlier suggest that* c. *30km of sinistral displacement occurred on the GGF, and that the inlier was uplifted by* c. *15km relative to the surrounding early Devonian rocks. Hence the inlier may formerly have been contiguous with the fault-bounded early Devonian Meall Fhuar-mhonaidh Outlier, now found adjacent to the GGF, 32km farther southwest. The deformation of this outlier can also be attributed to Acadian transpression.*

Acadian deformation and localised uplift were over by c. *393Ma when Eifelian-Givetian sandstones and conglomerates were deposited in the exhumed Rosemarkie Inlier. Evidence from here and from farther south in the Midland Valley suggests that Devonian sedimentation overlapped the early stages of the Acadian Event in Upper Emsian times. Thus, the transpressional event only lasted for a mere 6Ma in northern Scotland. As the Acadian Event related to Proto-Variscan plate-tectonic activity in the Rheic Ocean, it is deemed to mark the end of the Caledonian Orogeny.*

Introduction

The term 'Caledonian', derived from the Latin for Scotland, was first used in a tectonic sense in 1888 by Eduard Suess (1831–1914) in the second volume of his book *Der Antlitz der Erd*e (1888; Suess 1906). He referred to Caledonian 'pre-Devonian mountains' extending from Norway through Scotland to Ireland and Wales. Suess recognised that tectonic events had both geographical limits and time-related frameworks but he lacked the evidence to define the age of deformation and metamorphism. Haug (1900) subsequently described the concept of orogeny as 'the process of mountain-building', and recognised four major orogenies in the European geological record: the Huronian (Precambrian), the Caledonian, the Hercynian and the Alpine.

During the 20th century the term Caledonian Orogeny was widely used, but with varied meanings. A recent appraisal of its use was given by McKerrow *et al.* (2000), who concluded that it should be restricted in a palaeogeographical sense to encompass the tectonic or orogenic phases that affected rocks within, or bordering, the Iapetus Ocean. McKerrow *et al*. commented on the diachronous nature of several of the constituent phases, and noted that the orogeny included several arc–arc and arc–continent collisions and related plate tectonic events. Thus, the Caledonian Orogeny in Scotland began with rift-drift transition at around 580–570Ma, followed by the rapid formation of the Iapetus Ocean. The peak of tectonic activity occurred in early to mid-Ordovician times (*c.* 470Ma) and has been ascribed in the British Isles to a complex arc–continent collision and termed the Grampian Event.

Chew (this volume) has presented a synthesis of this event focussed on the evidence from the Irish Caledonides. Closure of the Iapetus Ocean to the south took place in Wenlock times (428–423Ma) when oblique docking of the eastern Avalonian microcontinent (England, Wales and southern parts of Ireland) with Scotland and the northern parts of Ireland occurred, generating the deformation and metamorphism of the Ordovician and Silurian largely turbiditic succession of the Southern Uplands (*see* Stone this volume). Hence, although oceanic tracts had disappeared from the palaeogeographic scene in Scotland by mid-Silurian times and exhumation of the orogenic welt had commenced, later compressional stages of the Caledonian Orogeny were still in progress elsewhere. Between *c.* 440Ma and 429Ma the Northern Highlands and Outer Hebrides were affected by the Scandian Event that was responsible for the generation of the Moine Thrust Belt and related deformation. This tectonic event resulted from Baltica–Greenland continental collision farther north, demonstrating the diachronous and varied nature of Iapetus Ocean closure. In mid-Silurian to early Devonian times the Highlands were marked by the intrusion of abundant granitoid plutons, associated with subduction farther south, and accompanied by rapid uplift. Transcurrent movements, mainly sinistral, took place along the Great Glen Fault (GGF), and probably also along the Highland Boundary. A series of north-east-trending sinistral faults were also generated in the Grampian and Northern Highlands at this time, e.g. the Loch Tay, Ericht-Laidon and Strathconon faults.

The nature of the plate tectonic events directly responsible for the main tectonic phases of the Caledonian Orogeny has been the subject of much speculation based on many studies in the Grampian and Northern Highlands of Scotland, Shetland, the Irish Caledonides and the Southern Uplands. Sadly, the presently

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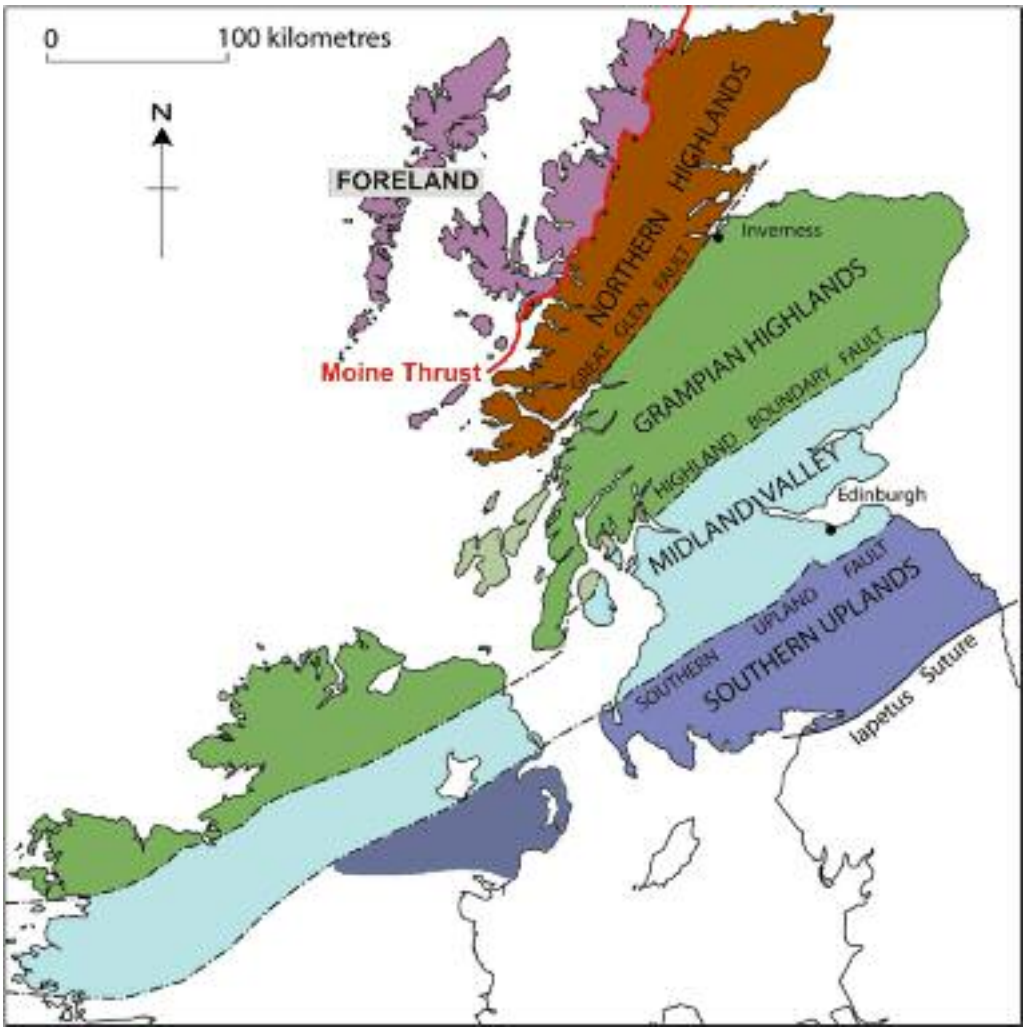


Figure 1 Tectonic framework of the Caledonides in mainland Scotland and Ireland showing the main terrane-bounding faults and the Moine Thrust.

exposed evidence of such events is limited — unsurprising, given that subduction, faulting, uplift, exhumation and erosion all combine to either conceal or destroy it. Fortunately, evidence for indenting arcs, sutures, thrust belts and other structural events is better preserved in parts of Newfoundland, east Greenland and Norway, giving us a wider and more comprehensive picture of the Caledonian Orogeny. A general pattern of rapid but variable oceanic crust–microcontinent–continent convergence can been recognised, linked mainly to subduction outboard from the Laurentian margin and ultimately the closure of the Iapetus Ocean. However, the detailed geometry, changing patterns of plate movements, palaeogeography and timing of these constituent events do still remain largely elusive. Following closure of the Iapetus Ocean and the mid-Silurian Scandian Event in northern Scotland the main tectonic framework of Highland Scotland was broadly as it is today. Lateral fault movements later modified the relative positions of the tectonomorphic belts, but the tripartite division into the Grampian Highlands, the Northern Highlands and the Foreland was in place at the end of the Caledonian Orogeny (Fig. 1).

The Acadian Event occurred in mid-Devonian times and was responsible for the main folding, cleavage formation and related metamorphism of the Cambrian, Ordovician and Silurian rocks in Wales, in the Lake District and in south-west and south-east Ireland. These areas of deformed Palaeozoic successions have traditionally been regarded at parts of the Caledonides and indeed McKerrow *et al.* (2000) included the Acadian Event in the Caledonian Orogeny.

The type area for the Acadian Event is in the northern Appalachians where western Avalonia collided with the Laurentian margin in the early Devonian (between 419Ma and 400Ma). Interestingly, no tectonic event has been detected in the coherent Devonian marine successions in Devon or in the Belgium Ardennes at this time. However, Woodcock *et al.* (2007) point out that Iapetus Ocean closure took place at least 20Ma before the Acadian Event, which in England, Wales and Ireland is closely bracketed between 400Ma and 390Ma. The Acadian Event is attributed to northward movement of the Midlands microcraton that impinged onto the adjacent sedimentary basins. Woodcock *et al.* (2007) show clearly that these tectonic events linked to the development of the Rheic Ocean, and the formation and migration of the peri-Gondwanan microcontinents. Although there was overlap between the events on the Gondwanan margin of Iapetus and the early stages of development of the Rheic Ocean, they argued that the Acadian Event should be regarded as proto-Variscan rather than end-Caledonian.

In this paper I will briefly describe the main structures related to the Scandian collision and the features generated during the subsequent Silurian–Devonian uplift and exhumation of the Caldonian Orogen — a time of widespread volcanism and emplacement of granitoid plutons, particularly in the Grampian Highlands. I will then show that Scotland, although distant from the main effects of the Acadian Event, did register its impact in both its Devonian stratigraphy and in the formation of localised structures. Deformation effects appear to have been focussed both along, and adjacent to, the main north-east-trending faults, namely the Southern Uplands, Highland Boundary and Great Glen faults. It will be argued that Acadian deformation resulted in the formation of the Rosemarkie Inlier, a lenticular body of Moine and Lewisianoid [*see below* The Scandian Event 3. — Ed.] rocks adjacent to the GGF bordering the Inner Moray Firth; deformation of the early Devonian Meall Fhuar-mhonaidh Outlier farther south-west; and the formation of the Strathmore Syncline and Sidlaw Anticline in the northern part of the Midland Valley. Acadian deformation is generally reflected in the Old Red Sandstone fluviatile and lacustrine successions in Scotland by an unconformity that separates early Devonian conglomerates, sandstones and siltstones from the overlying mid-Devonian and Upper Devonian sandstones and siltstones. As such, this surface marks the end of the Caledonian Orogeny in Scotland.

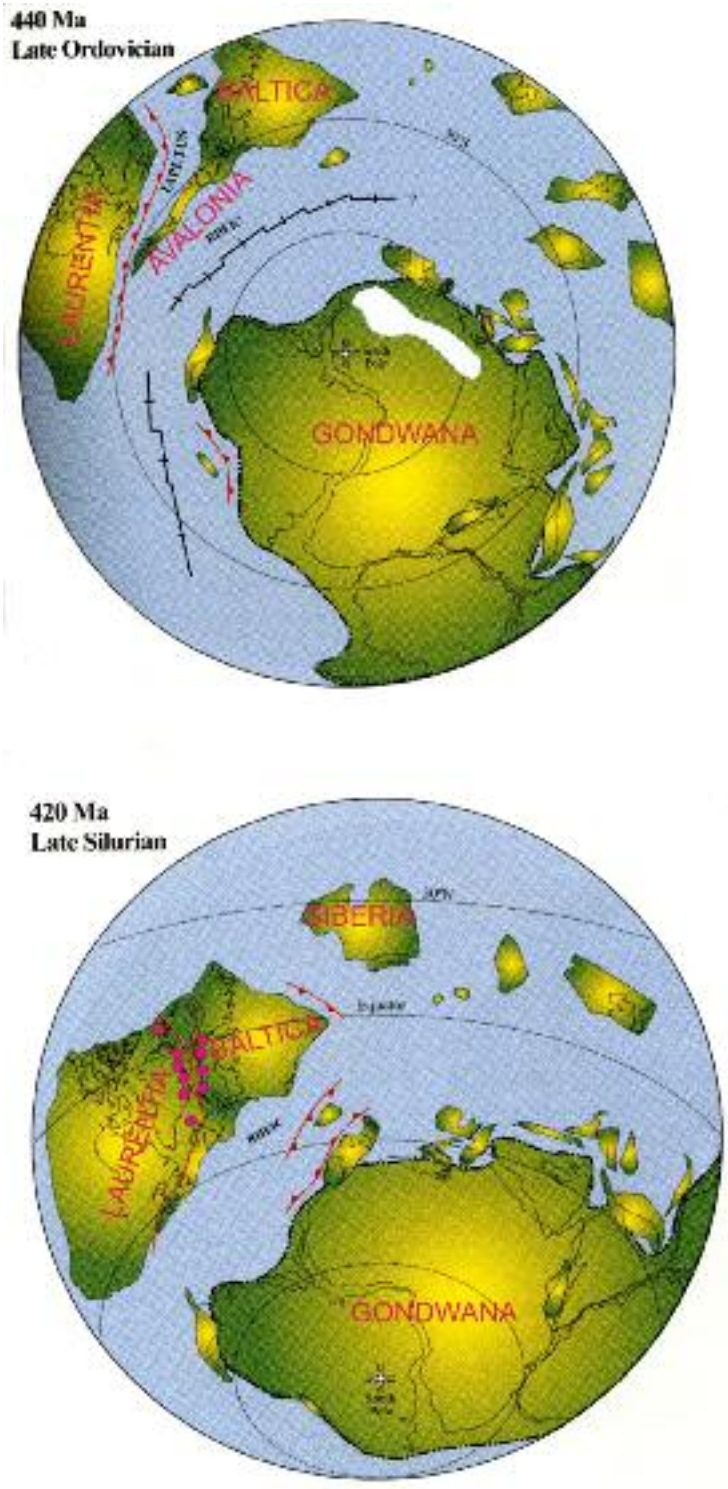


Figure 2 Palaeogeographical reconstructions illustrating the positions of the continents in the later phases of the Caledonian Orogeny at 440Ma and 420Ma; note that Avalonia includes Carolinia; areas affected by the Scandian Event that amalgamated Laurentia and Baltica into the continent of Laurussia are shown with a magenta dot ornament (modified after Cocks and Torsvik 2006).

The Scandian Event

The Scandian Event was generated when Baltica collided with Laurentia (east Greenland), closing the northern part of the Iapetus Ocean and creating the continent of Laurussia. Figure 2 shows palaoegeographical reconstructions by Cocks and Torsvik (2006) at 440Ma and at 420Ma. The palaeomagnetic evidence suggests that between Cambrian and mid-Silurian times Baltica effectively 'pirouetted' slowly 90° anticlockwise to collide with east Greenland, thus generating the extensive Scandian nappe stacks and related metamorphism that dominate the Greenland and Scandinavian Caledonides. It seems that north-west Scotland was caught up at the southern end of this tectonic collision. As a consequence, deformed and metamorphosed Neoproterozoic rocks of the Moine Nappe were overthrust to the west-north-west for some 50–100km over the older Foreland Lewisian gneisses and their Torridonian and Cambrian sedimentary cover, resulting in the formation of the Moine Thrust Belt.

The bedrock geology of north-west Scotland comprises three major tectonic elements:

1. The Foreland, which consists of Archaean and Proterozoic gneisses, termed the Lewisian Gneiss Complex, overlain unconformably by a cover sequence of Torridonian and Cambrian–Ordovician sedimentary rocks. The orthogneisses were largely derived from felsic, mafic and ultramafic intrusive protoliths. The Torridonian rocks are mostly fluviatile to lacustrine, red-brown arkosic sandstones with local conglomerates and minor siltstones and mudstones. They are late Mesoproterozoic and early Neoproterozoic in age and have not been metamorphosed. The overlying Cambro-Ordovician rocks comprise quartzites, in part with abundant worm burrow casts ('pipe rock'), potash-rich shales with dolomitic beds, and dolostones and limestones. This shallow marine shelf sequence can be traced with only minor stratigraphical changes from the north Sutherland coast south-west to Skye, but is also found in Greenland, Baltica and parts of Newfoundland.

2. The Moine Thrust Belt (or Zone), which extends from Loch Eriboll south-south-west to the Sleat Peninsula of Skye, forms a gently east-south-east-dipping structural succession of thrust and imbricated slices of the Foreland rocks, up to 11km wide, which in Assynt has been intruded by syenite plutons and abundant related minor intrusions. The thrust belt contains mylonitic rocks, found in its upper parts, but is characterised by its brittle deformation features. Major thrusts have transported different parts of the Foreland succession to the west-north-west with the older thrust nappes stacked above younger ones. The overall sequence of thrusting has juxtaposed earlier-formed nappes, spawned at deeper crustal levels, with those developed later at shallower crustal levels. Within the higher thrust sheets large-scale folds of the gneissose basement and sedimentary cover have been recognised, but more generally individual beds or sedimentary units have been stacked up and duplicated, commonly giving rise to an imbricate geometry (like tiles on a roof). The imbrication reflects the well-bedded and lithologically varied nature of the Cambro-Ordovician sequence and its response to the regional Scandian compression. In the southern part of the thrust belt thicker Torridonian units define large-scale recumbent folds and show evidence of greenschist facies metamorphism and local cleavage development.

3. The Moine Nappe lies in the hangingwall of the Moine Thrust (*sensu stricto*), a major dislocation within the Moine Thrust Belt that generally marks its eastern upper boundary. Within the Moine Nappe, which crops out over a large part of the Northern Highlands, are strongly deformed and metamorphosed metasedimentary rocks of the Moine Supergroup, originally deposited as

fluviatile to lacustrine and marine sandstones, siltstones and mudstones. The Moine and Torridonian successions are lithologically and stratigraphically similar, and were deposited during the early Neoproterozoic. Both successions unconformably overlie Archaean basement orthogneisses with subsidiary metasedimentary enclaves, but those underlying the Moine rocks show lithological (more mafic and ultramafic intrusions) and isotopic differences (general lack of Laxfordian reworking) to the Lewisian gneisses of the Foreland. Hence, they have been termed Lewisianoid to reflect their similar age and provenance but also to acknowledge they were formed at some distance from the Lewisian Gneiss Complex itself. The Moine and Torridonian successions exhibit similar detrital zircon age spectra and have been interpreted as laterally equivalent (Krabbendam *et al.* 2008). The Moine succession was intruded by metagranite sheets and by metadolerite dykes and sheets at *c.* 870Ma, shortly after its sedimentation. Both the sedimentary succession and the early igneous rocks show evidence of an extended deformational and metamorphic history (Mendum *et al.* 2009). In places there is evidence of deformation and metamorphism relating to a Knoydartian orogenic event at *c.* 820–780Ma and possible later metamorphism at *c.* 750–730Ma. The succession was at least partially affected by the Grampian Event at *c.* 470–455Ma and then again tectonically reworked during the Scandian Event at *c.* 440–429Ma.

The Moine Thrust Belt (MTB) has excited interest since Lapworth's ground-breaking work on the east side of Loch Eriboll in north Sutherland in 1882–3. Lapworth rapidly showed that the Moine rocks have been carried westwards over the Cambro-Ordovician rocks and underlying gneisses by means of thrusts, thereby generating mylonites and other fault rocks. This work resolved a long-standing controversy as to the nature of the relationship between the unmetamorphosed Foreland sedimentary rocks and structurally overlying metamorphosed and foliated Moine rocks. Archibald Geikie, who in 1882 had been appointed as Director General of the Geological Survey, was at first unconvinced by Lapworth's conclusions. However, from 1884 onwards he viewed geological mapping in the MTB as the key to understanding Highland geology. As a result, from 1883 to 1901 the Geological Survey mapped the belt in detail, work that was summarised in the Northwest Highlands memoir (Peach *et al.* 1907). The belt again became a focus for further studies in the 1970s and early 1980s with the recognition that it was a good place to work out the mechanics of thrusting and the complexities of its geometry (Elliot and Johnson 1980; Butler 1982; Coward 1983; Butler 2010).

It is not intended to provide a comprehensive account of the thrust belt here, but merely to focus on some of the more recent work carried out by the Geological Survey in Assynt and how that impinges on our understanding of its geological history.

The Traligill Transverse Zone

The geometry of the thrust belt is controlled by the number and magnitude of the basement Lewisian gneiss bodies that lie in the component thrust sheets and the thickness of the imbricated stacks of the various Cambro-Ordovician units. The relative abundance of basement gneiss sheets in Assynt has resulted in formation of the Assynt Culmination; here, the thrust belt reaches some 10–11km in width and more than 2km in structural thickness. Figure 3 shows the component thrust sheets in this area.

Figure 3 Map showing the component thrust sheets of the Moine Thrust Belt in the Assynt Culmination.

The culmination is transected by a west-north-west-trending sub-vertical zone of faults and thrusts that underlies Glen Dubh and the Traligill Valley, which Krabbendam and Leslie (2010) term the Traligill Transverse Zone. This faulted zone extends west-north-west of the thrust belt in the Foreland Lewisian gneisses as the Loch Assynt Fault, which seems to link to the Stoer Shear Zone farther west-north-west. Krabbendam and Leslie show that offset across the fault in the Foreland amounted to 1,200m sinistrally and 120m vertically (down to the north-east). In the higher Ben More Nappe the zone is manifest as the Bealach Traligill Fault, which has only offset the nappe and the overlying Moine Thrust by a few hundred metres. At lower structural levels the *en échelon* Gleann Dubh Fault has also displaced thrust features, implying *c.* 90m of lateral movement and 20m of downthrow to the north-east. Lower down in the thrust belt the Traligill Thrust forms a lateral ramp defining the north-east margin of a thick set of imbricated Durness group dolostones and limestones. This thrust dips moderately steeply to the south-south-west and strikes west-north-west, parallel to the main transport direction in the MTB.

Krabbendam and Leslie (2010) show that the Traligill Thrust is folded by the Droighinn Anticline, a major north-west-trending periclinal structure, which they interpret as generated by stacking of later-formed imbricate slices beneath. The Droighinn Anticline can be traced south into the Breabag Dome. What is clear is that the thrust geometry changes markedly across this Traligill boundary. To the north-north-east the Glencoul Thrust Sheet and associated thrust nappes are composed of thick slabs of Lewisian gneisses and the imbricated and repeated occurrence of the overlying Cambrian quartzites (Eriboll Formation). In contrast, to the south-south-east the Stronchrubie–Breabag Thrust System consists of numerous individual thrust sheets formed in the Cambrian quartzites in its upper part, but dominated by Cambro-Ordovician Durness Group dolostones and limestones in its lower part (Fig. 4, *opposite*). Krabbendam and Leslie (2010) show that the faulting post-dated deposition of the Cambro-Ordovician sequence, but predated the formation of the thrust belt. The fault offsets and resultant steps in the geological template were relatively minor, but the effects on the development of the thrust belt geometry were significant. It is recognised that there are considerable lateral changes in the nature of the basement and cover along the exposed length of the MTB and that these are at least in part responsible for its variable geometry.

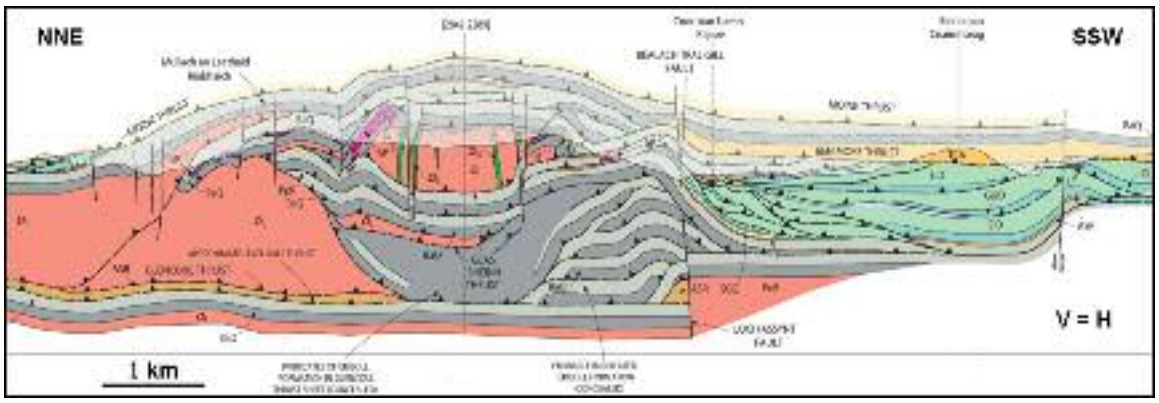
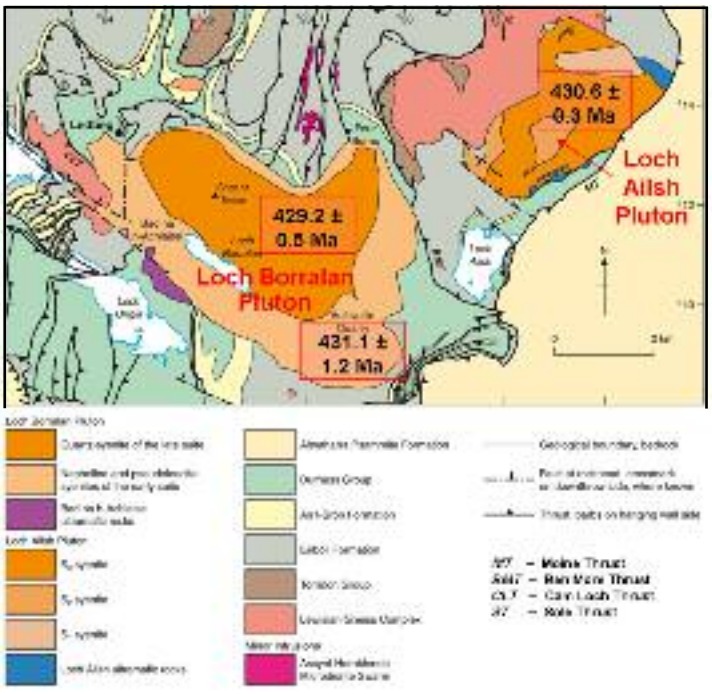


Figure 4 Cross-section normal to the thrust-transport direction across the Bealach Traligill Fault showing the lateral variations in thrust geometry within the Moine Thrust Belt in Assynt (modified after Krabbendam and Leslie 2010).

The Age of the Moine Thrust Belt

The presence of calc-alkaline igneous intrusions in Assynt has attracted the attention of petrologists and geochronologists for many years. Locally abundant sills, sheets and dykes and two syenite plutons, namely the Loch Borralan and Loch Ailsh plutons were intruded into the Assynt Culmination at or around the time of thrusting. The Loch Ailsh Pluton is locally foliated and was interpreted as being emplaced prior to the main brittle movements on the MTB. Its U-Pb zircon age of 439±4Ma (Halliday *et al.* 1987) was used to provide a maximum date for the main thrust movements. The Loch Borralan Pluton consists of an early phase of nepheline- and pseudoleucite-bearing syenites and a later phase of quartz syenite. Van Breemen *et al.* (1979a) obtained a bulk U-Pb zircon age of 430±4Ma for emplacement of the pluton, which was considered to post-date movement on the MTB. Although most of the calc-alkaline intrusions lie within the MTB, the Canisp Porphyry, a porphyritic quartz-microsyenite that forms extensive sills, is found only in the Foreland succession, albeit very close to the mapped trace of the Sole Thrust. Hence its emplacement was assumed to predate brittle thrusting movements, particularly the latest phases that link to movements on the Sole Thrust. Goodenough *et al*. (2006) obtained a U-Pb zircon TIMS age of 437±5Ma from the Canisp Porphyry. More recently Goodenough *et al.* (2011) have carried out further U-Pb zircon TIMS dating on these calc-alkaline intrusions and have reassessed their ages of emplacement (Fig. 5). The Loch Ailsh Pluton is now dated at 430.6±0.3Ma, and the early and later parts of the Loch Borralan Pluton are dated 431.1±1.2Ma and 429.2±0.5Ma, respectively.

Figure 5 Map of the syenite plutons in the southern part of the Assynt Culmination (Moine Thrust Belt) showing their ages of emplacement (modified after Goodenough et al. *2011).*



The Canisp Porphyry gave an age of 430.4±0.4Ma. This cluster of ages at *c.* 430Ma, provides good control on the younger limits of thrust movements, but removes any constraint on their maximum age. Freeman *et al.* (1998) obtained Rb–Sr muscovite ages from mylonitic rocks of the MTB south of Assynt suggesting that movements continued until *c.* 408Ma. Similarly, Dallmeyer *et al.* (2001) obtained Rb-Sr muscovite ages ranging from 427Ma to 413Ma from mylonitic rocks farther north in Sutherland. The Rb-Sr muscovite ages are at variance with those from Assynt suggesting that there may have been later localised reactivation of the MTB, and/or problems with interpretation of the isotopic data or systems.

Evidence for the Scandian Event in Moine rocks (Northern Highlands)

The Moine rocks in the southern part of the Northern Highlands can be structurally divided into a 'Flat Belt' in the east, a 'Steep Belt' in the centre and a more variable folded but overall gently dipping part in the west. The Steep Belt consists mainly of Glenfinnan Group pelites, psammites and semi-pelites with amphibolitic mafic bodies locally common. It represents a zone of greater deformation with large- and small-scale refolding of earlier thrusts, folds and fabrics. At its eastern margin in Glen Dessarry the Moine rocks are intruded by the Glendessarry Syenite Pluton, which contains xenoliths of the Moine rocks, some of which show tight, early folds. The intrusion itself is tightly folded into a sheath-like synform and is foliated and lineated. The syenite was originally dated by van Breemen *et al.* (1979b) at 456±5Ma (U-Pb zircon), but Goodenough *et al.* (2011) have revised this age to 447.9±2.9Ma. This supports the idea that the late main folding in the Steep Belt, previously termed D3, may well relate to the Scandian Event.

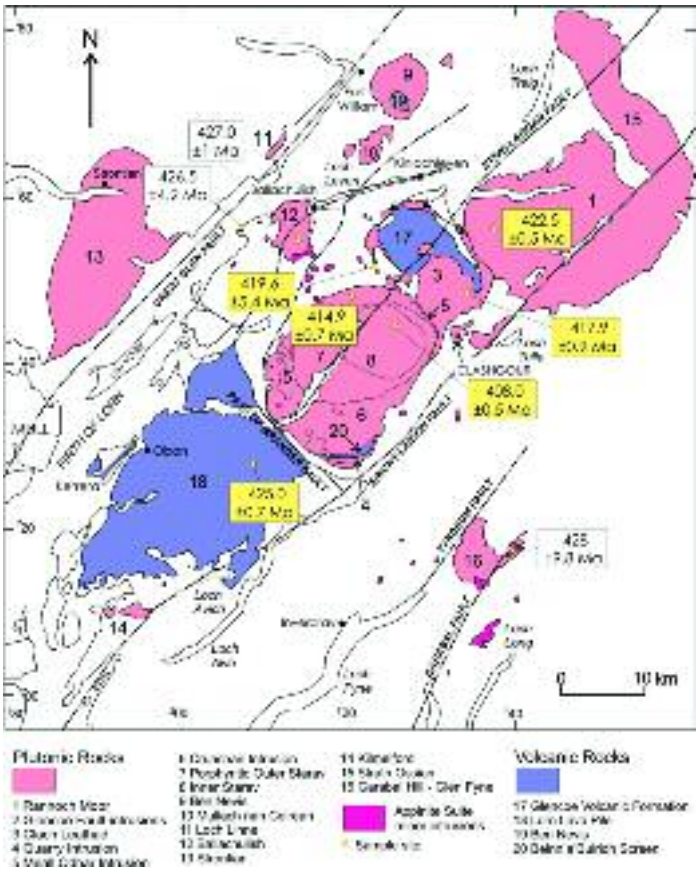


Figure 6 Map of the south-west part of the Grampian Highlands showing the plutons, dykes, other minor intrusions and related volcanic rocks; note that the Ben Nevis Dyke Swarm is omitted. Yellow boxes show recent U-Pb zircon ages; unshaded boxes show earlier published age data (from Neilson et al. *(2009).*

In Sutherland several granite intrusions that lie within the Moine succession carry a penetrative foliation orientated near parallel to that of the adjacent Moine country rocks. These sheeted intrusions are locally discordant to earlier folds and fabrics but lie close to or within ductile thrust zones, notably the Naver, Swordly and Skinsdale thrusts, and have been interpreted as emplaced synchronous with westward thrusting. Kinny *et al.* (2003) obtained U-Pb SHRIMP zircon ages from the granites, ranging from 429±11Ma (Strathnaver Granite) to 420±6Ma (Klibreck Granite). Kocks *et al.* (2006) obtained a similar U-Pb TIMS monazite age of 426±2Ma for intrusion of the Strath Halladale Granite. Thus, most of the ductile thrust zones in the Sutherland Moine rocks have been interpreted as being either of Scandian age or reactivating earlier formed thrusts during the Scandian Event. Goodenough *et al.* (2011) suggest that a re-interpetation of the data, which show evidence of Pb loss (particularly for the Klibreck Granite), would lead to revised ages closer to 430Ma.

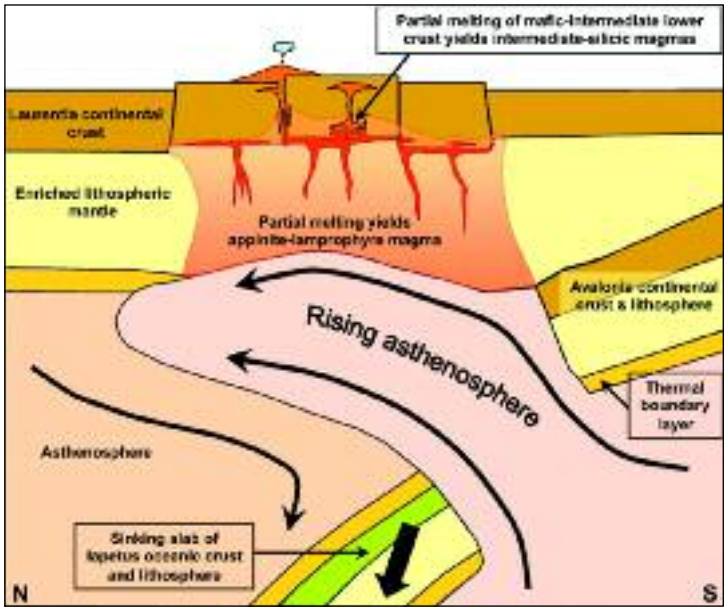
Mid- to late Silurian faulting, uplift and granite plutonism

Closely following on the Scandian Event there is evidence for significant sinistral lateral movements on the GGF and other north-east-trending sinistral transcurrent faults in the Grampian and Northern Highlands. Emplacement of the Clunes Tonalite Pluton, dated at 428±2Ma (U-Pb zircon TIMS), was interpreted as synchronous with sinistral lateral movements on the GGF (Stewart *et al.* 2001). Similarly the geometry of the Strontian and Foyers granitoid plutons, both of which lie adjacent to the GGF, is compatible with their emplacement coeval with lateral fault movements. North-east-trending faults are well developed across the Grampian Highlands with their formation also attributed to mid-Silurian times, probably reflecting the major change in plate kinematics taking place farther south beneath the Southern Uplands.

Jacques and Reavy (1994) postulated that a series of lower crustal ductile shear zones developed at this time, providing pathways for the ascent of granitoid magmas that resulted in the widespread plutonism focussed at *c.* 425Ma, particularly in the Grampian Highlands. The recent work of Neilson *et al*. (2009) on the mid- to late Silurian calc-akaline granitoid plutons and related dykes, sheets, lavas, etc of the south-west Grampian Highlands has clarified relationships between component bodies and timing of their emplacement. Neilson *et al.* (2009) present revised U-Pb zircon TIMS ages from several of these intrusions in the Loch Etive — Glencoe–Ben Nevis region. They also used geochemical data from the intrusions and adjacent Lorn lavas to infer petrogenetic relationships. Figure 6 shows a summary of their revised ages for the major intrusions.

Neilson *et al.* conclude that that there was an evolving sequence of plutonism from 427Ma to 407Ma, accompanied by crustal uplift. Many of the lavas show geochemical affinities with the abundant but small-scale appinitic and lamprophyric intrusions. Neilson *et al.* propose a model of slab break-off with a consequent uprise of hot 'dry' asthenosphere that melted enriched lithospheric mantle and thus forming repeated batches of appinite-lamprophyre magma (Fig. 7). Linked with partial melting of the lower crust, they suggest that this process resulted in the generation of the voluminous high Ba-Sr granitoid magmas. The Glencoe Caldera is one of the few remnants of a once more widespread volcanic province, typified by thick andesitic and dacitic lava flows. These large volcanic edifices have been uplifted and eroded and their roots intruded by the granitic plutons. Slab break-off may have resulted from either subduction resistance to

Figure 7 Schematic diagram illustrating a petrogenetic model for the formation of the Silurian granitoid putons of the Grampian Highlands. The model involves slab break-off, consequent rise of hot asthenosphere and partial melting of the lithospheric mantle. This is followed by pluton formation and emplacement into the upper crust, all accompanied by faulting and uplift (from Neilson et al. *(2009).*



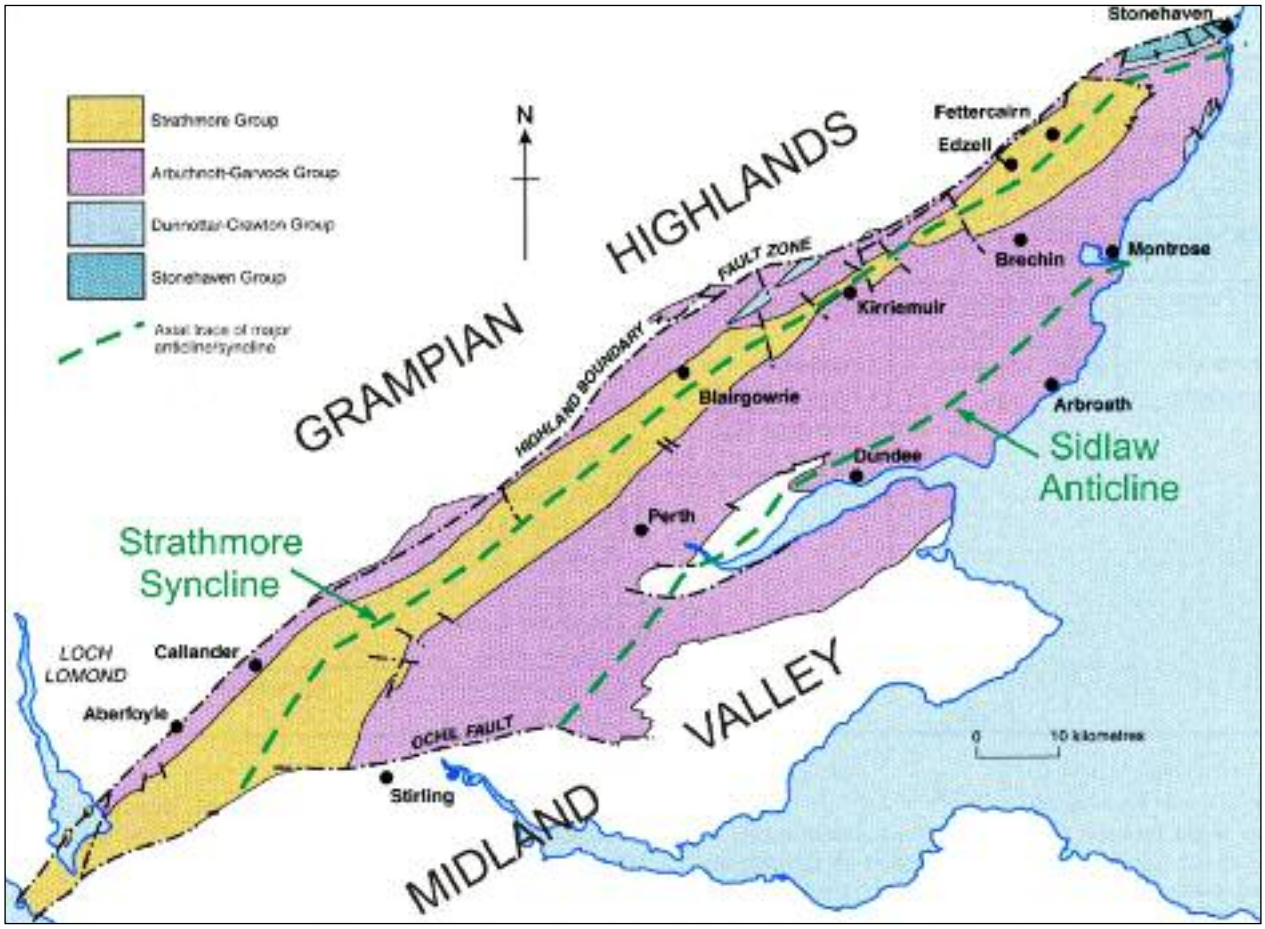


Figure 8 Map showing the distribution of the stratigraphical groups that make up the lower parts of the Old Red Sandstone Supergroup in the northern Midland Valley; the traces of the Strathmore Syncline and Sidlaw Anticline are also marked (modified after Browne et al. *2002).*

the ingress of continental Avalonia to the south-east, or from south-westerly lateral propagation of slab detachment linked to the Scandian Baltica–Laurentia collision.

Devonian sedimentation

Outliers of late Silurian to early Devonian Old Red Sandstone (ORS) sedimentary and volcanic sequences are preserved in several parts of the Grampian and Northern Highlands, but more extensive successions are present in the north-west part of the Midland Valley of Scotland and in the Moray Firth–Caithness region. The sediments, mainly sands, gravels and silts, were deposited under fluviatile to lacustrine conditions in a desert environment. In many instances the sequences are non-fossiliferous, but in parts fish and arthropod fauna are present, and plant remains, spores and arthropod traces also occur (Trewin and Thirlwall 2002). Unquestionably, the jewel in the crown is the varied flora and fauna preserved in the Rhynie hot spring system, linked to local andesitic volcanism, dated by Parry *et al.* (2011) at 411.5±1.3Ma (U-Pb zircon TIMS).

Although parts of the succession in the Stonehaven area are late Silurian in age, most of the ORS sequences are early Devonian (Lochovian to Emsian). Figure 8 shows the distribution of the groups within the Old Red Sandstone Supergroup in the Midland Valley and Figure 9 *(overleaf)* illustrates the component formations. Volcanic rocks, mostly andesite, basaltic andesite and basalt lavas with local agglomerate and tuff occur widely in the succession, notably in the Ochil and Sidlaw Hills. Volcanic clasts are also common in the conglomerates and sandstones of the Stonehaven and Dunnotar-Crawton groups. A dacitic welded tuff, the Lintrathen Tuff, occurs in Glen Isla, north-west of the Highland Boundary Fault. The tuff has been dated at 415.5±5.8Ma (Rb-Sr, biotite; Thirlwall 1988). This distinctive unit, locally up to 160m thick, has been correlated laterally with the Crawton Volcanic Formation that occurs widely in the Midland Valley succession southwest of Stonehaven (Fig. 9). As such it forms a chronostratigraphical unit within the succession and a link across the Highland Boundary Fault.

At higher stratigraphical levels in the Old Red Sandstone succession sandstone and mudstone formations are more common. The Cromlix Mudstone Formation is a widespread unit recognised across the Midland Valley. However, the uppermost Strathmore Group units are sandstone and locally conglomerate formations. The Gannochy Conglomerate Formation and Strathfinella Hill, Uamh Bheag and Bracklinn Falls conglomerate members all represent higher-energy deposits that lie adjacent to the Highland Boundary. In the Strathfinella Conglomerate Member (Teith Sandstone Formation) the cobbles are lithologically varied but include igneous and metamorphic clasts that can be matched to outcrops within the Grampian Highlands to the north-west. This suggests that derivation from an uplifted area of Dalradian rocks and granitic plutons northwest of the Highland Boundary Fault Zone, and deposition of local fanglomerate units in the marginal areas of the Midland Valley. These youngest rocks are Emsian in age.

In Ross and Cromarty and Caithness early Devonian rocks are represented by the Struie Group in the Beauly-Dingwall region,

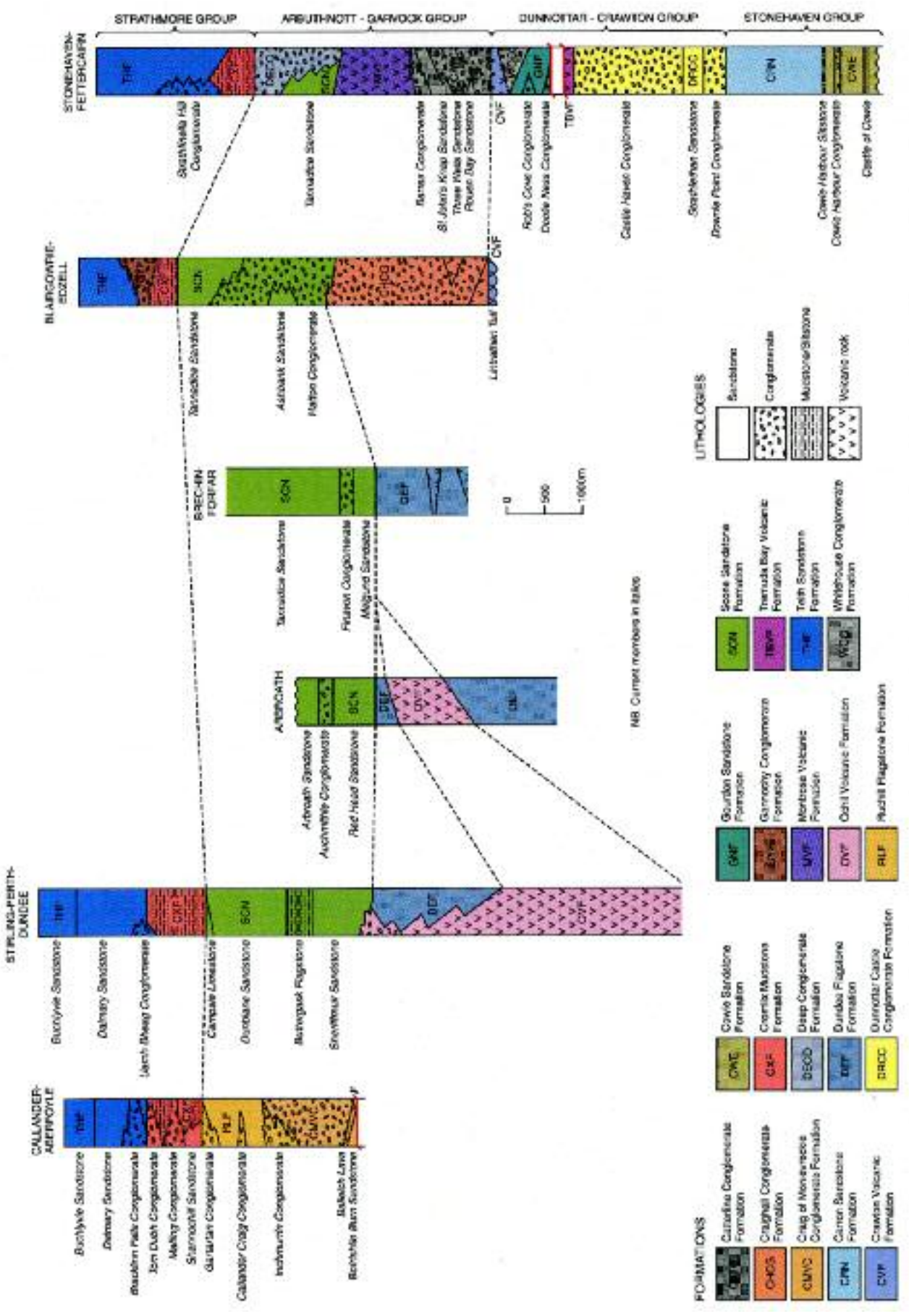
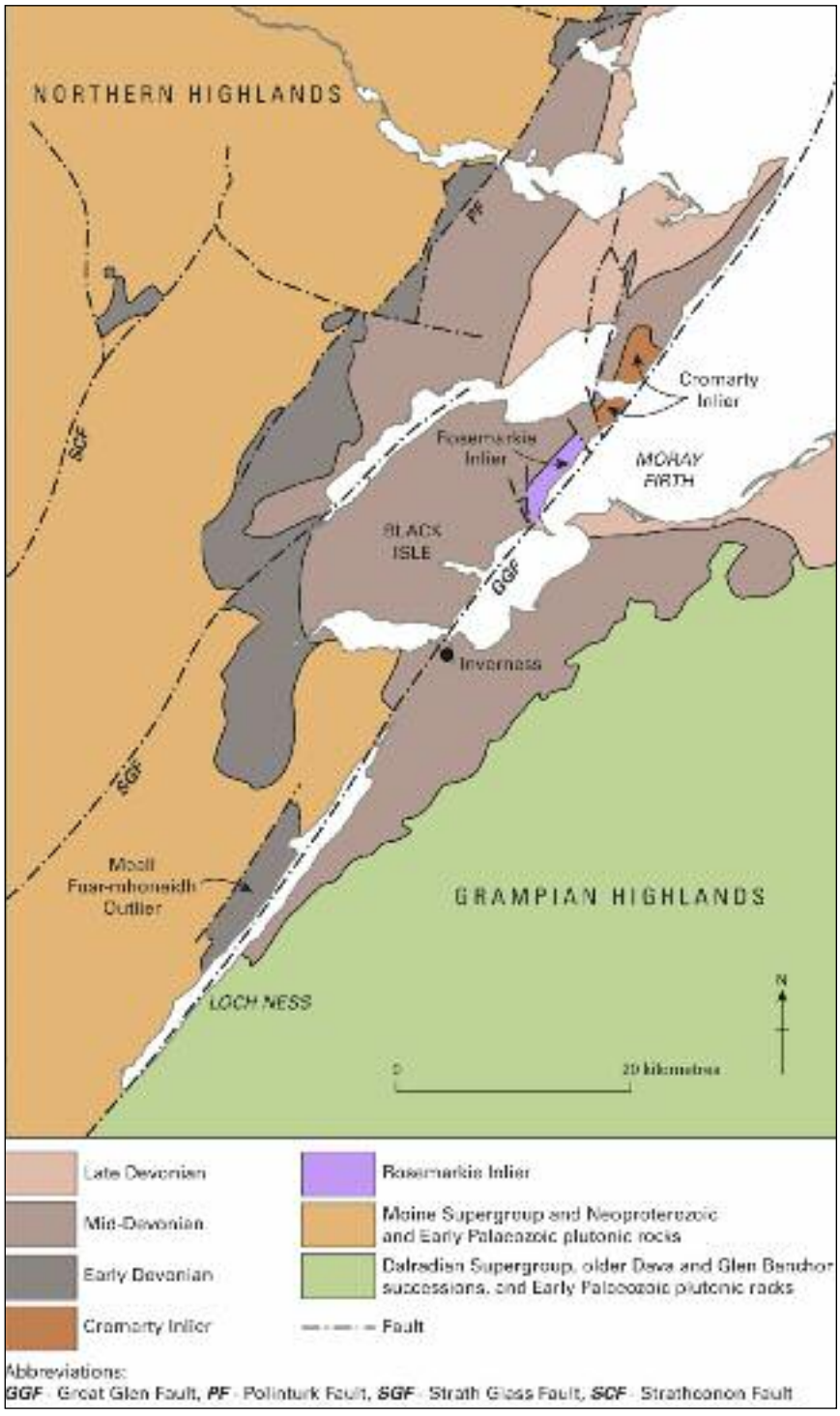


Figure 9 Fence diagram showing the component formations and members of the late Silurian to early Devonian parts of the ORS Supergroup in the northern Midland Valley (from Browne et al. *2002).*

and the conglomerates, sandstones and mudstones found in the Golspie and Badbea basins and the Sarclet Inlier. The Struie Group has basal conglomerates and breccias, succeeded by *c.* 400m of olive-grey to black bituminous shales with impure limestones. The organic shales developed in a restricted lake environment and contain H_2S. Thus, they have a foetid odour and are the source of the sulphur 'spa' waters at Strathpeffer. Further early Devonian lacustrine shale sequences lie offshore in restricted fault-bounded basins beneath the Mesozoic rocks of the Moray Firth (Marshall and Hewett 2003). These Lower ORS units are overlain by mid-Devonian (Eifelian–Givetian) sandstones, siltstones and mudstones with fish beds that form part of the wider Orcadian Basin lacustrine succession. In parts the early and mid-Devonian sequences are separated by an unconformity, but Rodgers *et al.* (1989) interpret this break as only of local significance, viewing the succession as effectively continuous.

Some 30km south-west from Inverness and overlooking the Great Glen is the hill of Meall Fhuar-mhonaidh, formed of massive conglomerates that from part of the eponymous outlier of early Devonian rocks that measures 15km long × 3km wide (Fig. 10). The *c.* 2km thick sequence consists of conglomerates, sandstones and siltstones and was mapped and described by Mykura and Owens (1983) (Fig. 11, *overleaf*). Sedimentary features and the rapid facies variations suggest that the sediments were deposited rapidly in a small fault-bounded basin. Minor plant fossils and some spores from its upper parts suggest it is late Emsian to early Eifelian in age. At the north-east extremity of the inlier near the top of the stratigraphical sequence is a thick clast-supported, coarse-grained, breccio-conglomerate unit, termed the Craig Nay Conglomerate. Its origin is interpreted by Mykura and Owens as a proximal debris flow derived from the east. Angular clasts from 500mm to 700m are common, and consist mainly of grey psammite and pink to orange leucogranite. Like the early Devonian rocks farther north in Easter Ross, the sequence shows evidence of limited folding and thrusting (Underhill and Brodie 1993).



The Rosemarkie Inlier

The Rosemarkie Inlier is a small fault-bounded lens of interleaved Moine psammites and semipelites and Lewisianoid felsic and mafic orthogneisses that lies adjacent to the GGF (*see* Fig. 10). It also contains some amphibolitic mafic pods and numerous distinctive pink leucogranite veins and pods. Early Devonian sandstones and shaly mudstones lie in faulted contact with the basement rocks on the south-west side of the inlier, but both are unconformably overlain by mid-Devonian sandstone and conglomerate (Fig. 12, *page 47*). The leucogranite veins range from millimetres to some 5m thick (typically 0.3–1m) and are locally discordant to the banding and sub-parallel foliation in the host gneisses and psammites. However, both the Archaean and Proterozoic basement rocks, and the leucogranite veins, are strongly deformed and tightly folded, with three distinct fold phases affecting the veins (Rathbone and Harris 1980). The related foliations are generally steeply dipping and a north-east-plunging rodding lineation is locally well developed. The leucogranite emplacement has been dated from monazite at 397.6±2.2Ma, with acicular zircons giving a compatible concordant U-Pb TIMS age of 400.8±2.6Ma (Mendum and Noble 2010). Complex zoned zircons from two tonalitic gneisses gave concordant U-Pb LA-MC-ICP-MS ages between 2720Ma and 2930Ma, confirming the Archaean (Badcallian) origin of the gneisses.

Figure 10 Map of the generalised geology of the area round Inverness showing the positions of the Rosemarkie and Cromarty inliers and the Meall Fhuar-mhonaidh Outlier (contains Ordnance Survey data © Crown Copyright and digital rights, 2012).

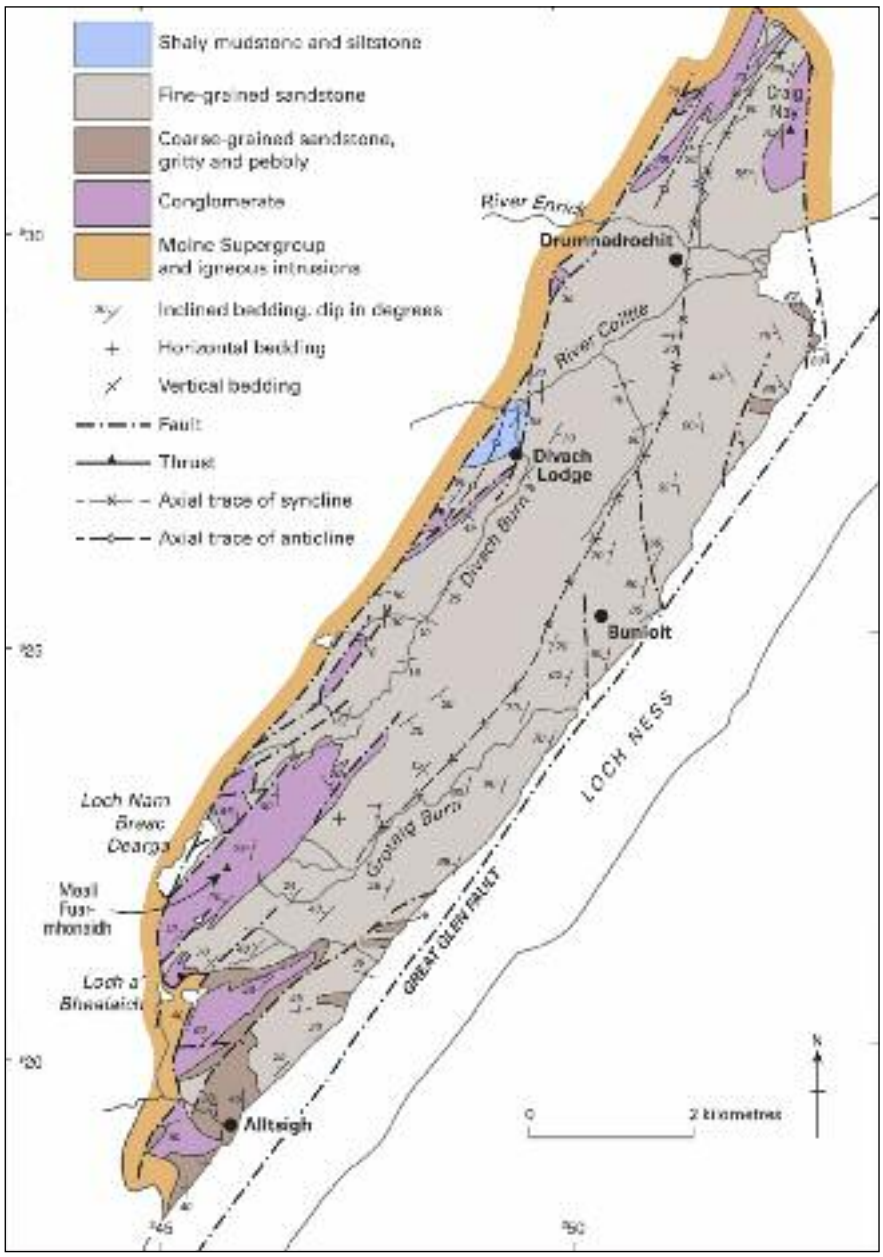


Figure 11 Geological map of the early Devonian Meall Fhuar-mhonaidh Outlier showing the main lithological units and internal structure (modified after Mykura and Owens 1983; contains Ordnance Survey data © Crown Copyright and digital rights, 2012).

One of the gneisses showed evidence of zircon growth and isotopic resetting at *c.* 1745Ma, indicative of Laxfordian reworking.

Acadian transpression effects along the GGF

The presence of leucogranites is largely confined to the Rosemarkie Inlier; only minor examples are found in one or two other places along the GGF zone. The association of leucogranite veining with transcurrent faults and some large-scale mylonitic zones has been recorded in several parts of the world; in many examples lateral or oblique fault movement and generation of leucogranites seem to be coeval. At Rosemarkie, emplacement is interpreted to mark the onset of Acadian transpression and sinistral strike-slip movement on the GGF. Mendum and Noble (2010) argue that the Rosemarkie Inlier was extruded obliquely as an elongate 'pip', generated at a restraining bend in the GGF as the locus of fault movement migrated north-westward. They show that the structural data from the inlier are compatible with a transpressive origin. The main foliation dips generally steeply to the south-east, but ranges to moderately eastward. Its mean pole lies some 10° clockwise from that of the GGF. The lineation, represented as prominent quartz rodding in the leucogranite, plunges moderately north-east (mean value 37° to 050). Rathbone (1980) measured the shape of the deformed quartz aggregates in the leucogranite, and assuming they were roughly equant when the granite was emplaced, derived a prolate finite strain ellipsoid value of X:Y:Z = 18:2.5:1. Note that few directional indicators are present in the inlier, and those present indicate contrary senses of movement, probably reflecting the long and complex history of the fault zone.

The inlier is unconformably overlain by mid-Devonian conglomerates and sandstones, and if this prolate strain can be taken as representative of the Acadian deformation of the whole inlier, then an estimate the amount of translation and uplift can be obtained. Taking the inlier's current dimensions (*c.* 2km wide) and restoring it to an unstrained state, suggests that a minimum of *c.* 29km of sinistral movement and *c.* 15km of uplift occurred during Acadian transpression (see Mendum and Noble, 2010 for details). The *c.* 15km of uplift would accord with the probable lower amphibolite grade metamorphic conditions implied by the fold structures and related biotite-bearing fabrics and mineralogy seen in the currently exposed outcrops. Interestingly, it would also place the interleaved Moine and Lewisianoid rocks approximately down dip from the outcrop of the Sgurr Beag Thrust around Garve and on the western flank of Ben Wyvis, where similar lithologies and relationships are exposed. Extrusion of the inlier is restricted realistically to a time period of *c.* 5Ma (398–393Ma), placing limits on the rates of lateral and vertical movement on the GGF. These would be of the order of 6mm/year and 3mm/year, respectively, making Acadian transpression a tectonically rapid but localised event. However, such values are in accord with published rates for fault movements in other parts of the world.

Restoration of the sinistral lateral movement also places the Rosemarkie Inlier close to the north-east end of the Meall Fhuar-mhonaidh Outlier prior to Acadian lateral movements on the GGF. Hence the Craig Nay Conglomerate could be derived from erosion of the inlier, albeit overlapping its initial stages of extrusion (Fig. 13, *opposite*). This would imply that Acadian deformation was coeval with the final stages of deposition of the Old Red Sandstone sequence in the Meall Fhuar-mhonaidh Outlier with both occurring in the late Emsian, an age that agrees with the palaeontological evidence in the outlier and leucogranite emplacement in the inlier.

The structure in the outlier, which lies 32km south-west of the Rosemarkie Inlier, is also compatible with Acadian transpression. Figure 11 shows the fold traces and interpreted thrusts mapped by Mykura and Owens (1983). They constructed cross-sections that showed how deformation was concentrated close to the trace of the GGF, with an overall shortening of *c.* 25% across the outlier.

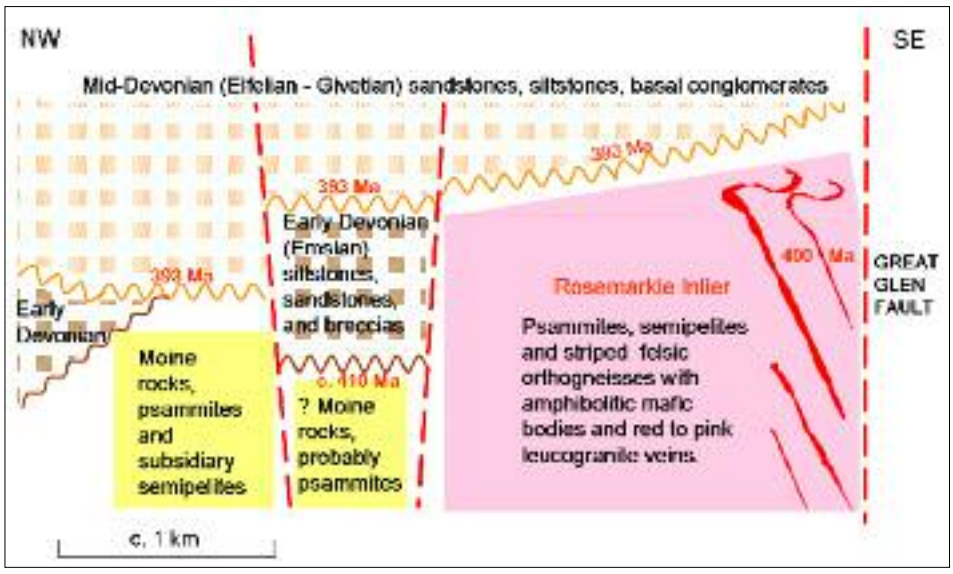

NW
SE
Mid-Devonian (Eifelian - Givetian) sandstones, siltstones, basal conglomerates
393 Ma
393 Ma
393 Ma
Early Devonian
Early Devonian (Emsian) siltstones, sandstones, and breccias
c. 410 Ma
400 Ma
GREAT GLEN FAULT
Rosemarkie Inlier
Psammites, semipelites and striped felsic orthogneisses with amphibolitic mafic bodies and red to pink leucogranitic veins.
Moine rocks, psammites and subsidiary semipelites
? Moine rocks, probably psammites
c. 1 km

Figure 12 Diagrammatic cross-section through the Rosemarkie Inlier showing the main geological elements and their relationships to the bounding faults (scale is approximate).

Small thrusts were mapped in the south-west part of the outlier. Although such structures may be of Mesozoic age their geometry defines a positive 'flower' structure compatible with Acadian transpression focussed on the GGF. Similar structures have been documented in Easter Ross where Underhill and Brodie (1993) showed from seismic and well data that the uppermost mid-Devonian marker was folded and faulted linked to Permo-Carboniferous inversion related to movements on the Glaick-Polinturk Fault. Farther north they interpreted the Struie Thrust as a similar age structure but its geometry is also compatible with Acadian transpression. The waning of Acadian effects northward may well be reflected in the decreasing angular relationship between the Lower ORS and overlying Middle ORS. In Caithness the two successions become conformable.

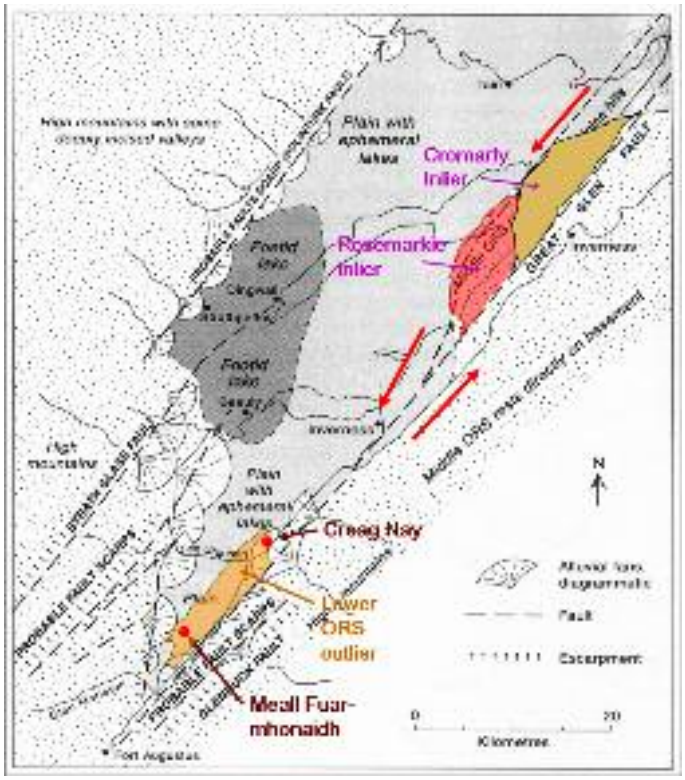
The Cromarty Inlier is another fault-bounded kilometre-scale 'pip' that lies immediately north-east of the Rosemarkie Inlier, again adjacent to the GGF. It also consists of uplifted basement onlapped by mid-Devonian conglomerates, but in this case composed of Moine rocks with pegmatitic granite lenses and veins. Its occurrence may represent a further step-over of the GGF to the north-west, but with less uplift, thereby exposing higher structural levels than at Rosemarkie. The Moine rocks are similar to those of the Loch Eil Group in the main Northern Highland Moine outcrop.

Evidence for Acadian deformation in the Midland Valley

The Midland Valley of Scotland is bounded on its north-west side by the Highland Boundary Fault Zone (HBFZ) and on its south-east side by the Southern Uplands Fault (SUF) (Fig. 14, *overleaf*). Early Devonian rocks are folded and fractured and the age of deformation is constrained by unconformably, overlying late Devonian sedimentary units. This mid-Devonian (Acadian) deformation was apparently localised along the main terrane-bounding faults and resulted in the formation of major and intermediate-scale folds, most notably the Strathmore Syncline and Sidlaw Anticline. Note that fold tightness increases as the HBFZ is approached. Hence, the Strathmore Syncline, whose axial trace runs sub-parallel to the HBFZ (*see* Fig. 8), has a steep to sub-vertical north-western limb and a more gently dipping south-eastern limb. The related Sidlaw Anticline is an altogether more open structure. There is also evidence for Acadian lateral movement on the HBFZ in that the Linthrathen Tuff, which crops out north-west of the fault zone, is apparently displaced sinistrally by 34km, relative to the equivalent unit in the Midland Valley, the Crawton Volcanic Formation. As noted above, the latter stages of Lower ORS sedimentation overlapped relative vertical movements on the HBFZ, with the uplifted Highland area shedding coarse detritus into the Midland Valley ORS succession during the later part of the Emsian (*see* Fig. 9). Jones *et al.* (1997) demonstrate that formation of the Strathmore Syncline and Sidlaw Anticline was a consequence of Acadian transpression, focussed on the HBFZ. They assessed the overall bulk shortening as 10–15% and attributed most of this to vertical stretching with minor sinistral faulting accounting for the lateral stretching element.

Lower ORS sandstones, conglomerates, and andesitic and basaltic volcanic rocks also crop out in various inliers near the south-east margin of the Midland Valley (Smith 1995) (*see* Fig. 14). Similar volcanic rocks in the Pentland Hills yield a Lochkovian age of *c.* 413Ma (Thirlwall 1988). The sequence reaches more than 2.5km thick locally in the Hagshaw Hills area,

Figure 13 Palaeogeographical reconstruction of the Lower ORS (early Devonian) environments in Easter Ross and the northern part of the Great Glen. The present outcrops of Rosemarkie and Cromarty inliers and the Meall Fhuar-mhonaidh Outlier have been added. The red arrows signify sinistral Acadian movements. Note that a post-Devonian dextral transcurrent movement of 27km along the GGF has been reversed (see two positions of Inverness) (modified after Mykura and Owens 1983).



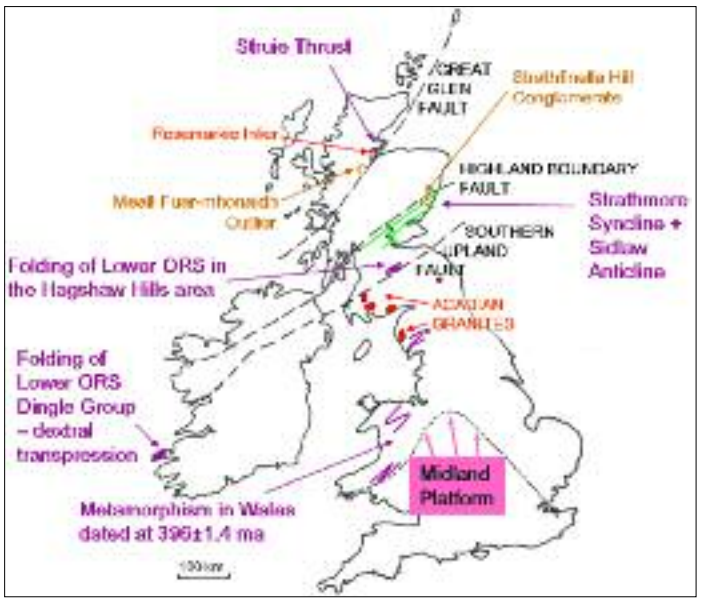

Strathmore
Syncline +
Sidlaw
Anticline
Folding of Lower ORS in the Hagshaw Hills area
Folding of Lower ORS Dingle Group – dextral transpression
Midland Platform
Metamorphism in Wales dated at 396±1.4 ma

Figure 14 Acadian structures and related sedimentary and igneous features in the British Isles.

where it is deformed into kilometre-scale, asymmetrical anticlines and synclines. These folds form an *en échelon* array whose axes trend north-east to east-north-east, slightly oblique (clockwise) to the neighbouring SUF. Limited thrusting to the south-east is also recorded (Smith 1995). He attributed this deformation to mid-Devonian (Acadian) sinistral transpression, whose age is again constrained by unconformably overlying Upper Devonian and Carboniferous strata. Floyd (1994) suggested that a mid-Devonian sinistral offset of 12km along the SUF could explain the present disposition of the Ordovician (Caradoc) Tappins Group and Marchburn Formation in the area north of the Loch Doon Granite Pluton.

Acadian deformation — the regional picture

The type area for the Acadian Orogeny is in Nova Scotia, where it is attributed to the collision of the western Avalonian microcontinent with the eastern margin of Laurentia. It is one of a series of Lower Palaeozoic events that occurred as a result of the repeated accretion of continental crust and oceanic arcs to the Laurentian margin in Newfoundland, Nova Scotia and New England, and in the more south-western parts of the Appalachian chain (Murphy *et al.* 2011). These peri-Gondwanan terranes, which include Ganderia, Avalonia, Carolinia and Meguma, were detached from northern margin of Gondwana, starting in the late Cambrian and early Ordovician, when the Rheic Ocean began to open rapidly. Nance *et al.* (2010) contend that this rift-drift transition occurred coeval with the onset of major subduction on the north-west side of the Iapetus Ocean at *c.* 510Ma. These narrow, lenticular and 'ribbon' microcontinental terranes tracked across the narrowing Iapetus Ocean to collide with the Laurentian margin in North America. Thus, together with older postulated peri-Laurentian microcontinental and oceanic arc terranes — e.g. the Dashwoods Terrane — they were the main agents of tectonic deformation in the Caledonian Orogeny in the Appalachians.

These collisions gave rise to the Taconic (495–450Ma), Salinic (442–425Ma), Acadian (419–400Ma) and Neoacadian (380–370Ma) orogenic events (Murphy *et al.* 2011). Hence the distinction between the Caledonian and Variscan is blurred with closure of Iapetus completed by 425Ma. In the British Isles it is easier to make a distinction between events linked to the Iapetus Ocean and those linked to the Rheic Ocean. Caledonian orogenesis in Scotland resulted from the collision of Cambrian to early Ordovician outboard arcs and possibly small microcontinental fragments with the Laurentian margin resulting in the Grampian Event but no peri-Gondwanan terranes were involved until the docking of Eastern Avalonia and consequent closure of the Iapetus Ocean at *c.* 423Ma. The only other tectonic agent was the Baltica–Laurentia collision that gave rise to the Scandian Event in northern Scotland, and in Greenland and Scandinavia. Significant post orogenic uplift occurred in Highland Scotland from *c*. 430Ma accompanied by major grantic plutonism. Hence the Acadian effects were short lived, linked to proto-Variscan events that resulted from plate tectonic re-organisation in the Rheic Ocean.

In England and Wales the Acadian Event is bracketed between 400Ma and 390Ma and was responsible for the formation of the pervasive folding and related cleavages in the Ordovician and Silurian rocks of Wales and the Lake District (Woodcock *et al*. 2007). The event is generally attributed to northward movement of the Midland Platform or microcraton that generated compression in the available sedimentary basins (*see* Fig. 14). The related short-lived northerly subduction gave rise to limited plutonism now manifest as granitic plutons in the Lake District and Southern Uplands. Deformation was orthogonal in Wales, and Sherlock *et al.* (2003) obtained a $^{40}Ar/^{39}Ar$ age of 396±1.4Ma from a muscovite in the main cleavage. Although deformation in Scotland was represented by localised sinistral transpression, in the Dingle Peninsula in the west of Ireland Acadian deformation of early Devonian sedimentary rocks resulted from dextral transpression (Meere and Mulchrone, 2006). The details of the plate tectonic geometry and movements within and marginal to the Rheic Ocean to the south are unclear, but there seems little doubt that the Acadian Event in the British Isles was a product of such proto-Variscan activity. Woodcock *et al.* (2007) present differing subduction models for the event, showing both northward and southward subduction as feasible mechanisms. However, all authors agree that Iapetan subduction had ceased with only the remnants of the subducted plates still present at depth below the Iapetan Suture and adjacent areas.

Farther north-east in Baltica there is evidence of an extended history of Devonian uplift and exhumation of the Western Gneiss region of Norway from at least 410Ma to 370Ma (Andersen 1998; Johnston *et al.* 2007). There is no sign of any mid-Devonian compressional event. Within the Caledonides of Baltica are several large sinistral transtensional basins infilled with Devonian sandstones and conglomerates and underlain by major extensional dislocations (Osmundsen and Andersen 2001). This is in agreement with Dewey and Strachan (2003) who argue that sinistral transtension prevailed during most of the late Silurian and early Devonian in the Caledonides of Scotland and Ireland, Baltica, Greenland and Spitzbergen.

Conclusions

The later phases of the Caledonian Orogeny in Scotland were strongly influenced by plate tectonic events either to the north, where Baltica collided with Laurentia, generating the Scandian Event, or to the south, related to Iapetan closure and the formation of the Southern Uplands. The effects of the Scandian Event are best seen in the Moine Thrust Belt and in parts of the Moine Nappe of the Northern Highlands.

The late Silurian and early Devonian marked a *c.* 30Ma period of orogenic uplift in the Northern Highlands and Grampian Highlands, accompanied by the emplacement of voluminous granitoid igneous intrusions. The more recent dating of plutons and related volcanic rocks, notably in the south-west Grampian Highlands, has provided good constraints on these processes. Uplift was accompanied by sinistral movements on the major terrane-bounding faults in the Highlands and by the generation of several subsidiary transcurrent faults. Fault movements were largely transtensional but there were times of localised transpression. The fluvial and lacustrine early Devonian sedimentary sequences deposited in the Midland Valley and in smaller basins within the Highlands preserve a partial record of this exhumation and fault movements.

The Rosemarkie Inlier, adjacent to the GGF just north-west of Inverness, consists of Moine psammites and semipelites and Lewisianoid felsic and mafic gneisses, all intruded by abundant pink leucogranite veins. Monazite and zircon U-Pb TIMS data from the leucogranite veins show that they were emplaced into the older basement rocks at *c.* 399Ma (Mendum and Noble 2010). The veins are discordant to the early planar fabrics and post-date Moine and Lewisianoid interleaving, but are strongly deformed and folded by three structural phases. Metamorphic assemblages and structural style are compatible with their formation at depths of 12–15km. The inlier is overlain unconformably by mid-Devonian (Eifelian–Givetian) sandstones and conglomerates whose deposition commenced at *c.* 393Ma; thus deformation and exhumation are restricted to a maximum time frame of 6Ma duration.

The structure of the Rosemarkie Inlier is dominated by a generally steep north-east-trending foliation, a moderately north-east-plunging lineation and strongly constrictional strains (Rathbone 1980). These features are compatible with its extrusion as an elongate 'pip' at a sharp restraining bend of the GGF during sinistral transpression. Hence, the Rosemarkie and adjacent Cromarty inliers represent fault-bounded step-overs, formed as the locus of sinistral lateral movement on the GGF migrated onto sub-parallel faults farther to the north-west.

During the early Devonian (Emsian) the Rosemarkie Inlier may have been situated adjacent to the Meall Fuar-mhonaidh Outlier, now sited some 32km away to its south-west. The Lower ORS sequence in the outlier contains a highly proximal conglomerate unit at its north-east end, whose clasts match the main lithologies of the Rosemarkie Inlier. It is proposed that the final stages of Lower ORS sedimentation in the outlier overlapped with the initial exhumation of the inlier, and thus the onset of significant lateral fault movement at *c.* 399Ma. The 32km offset is broadly compatible with the strain values obtained from the deformed leucogranites and the structural geometry in the inlier.

The mid-Devonian sinistral transpressional event identified at Rosemarkie is interpreted as an Acadian Event, generated by a short-lived, northward-directed compressional pulse between 400Ma and 390Ma. This deformation is related to the collision of an Armorican microcontinent, the Midlands microcraton, with other parts of Avalonia (Woodcock *et al.* 2007). In Scotland, deformation was focused on the main terrane-bounding fault zones, namely the Southern Upland, Highland Boundary and Great Glen fault zones. It was generally partitioned into sinistral strike-slip movements and related orthogonal compression. Intensity of deformation was greatest adjacent to the fault zones and decreased with distance away from them. Deformation was preferentially taken up by the Lower ORS sequences in nearby extensional basins. Positive flower structures were formed on the north-west side of the GGF in the Meall Fuar-mhonaidh Outlier and in the Lower ORS succession in Easter Ross. The Lower ORS–Middle ORS unconformity can be traced northward as far as Caithness, possibly reflecting the waning effects of the Acadian Event.

Mid-Devonian (Acadian) sinistral transpression marked a significant change in the kinematics of the GGF. Prior to this event in the late Silurian and early Devonian the fault appears to have been a planar structure and a focus for sinistral lateral movements, firstly in transpression (Stewart *et al.* 2001), but mainly in transtension (Dewey and Strachan 2003). The end Caledonian uplift and formation of small-scale basins in the early Devonian altered the structural geometry, particularly in the Moray Firth area. Hence, when, north-directed Acadian compression reached Highland Scotland, the GGF formed a restraining bend to facilitate the migration of lateral movement north-westward. This pattern of north-west fault migration was subsequently repeated in late Palaeozoic and Mesozoic times during transtensional and transpressional events, both sinistral and dextral.

The wider pattern of the Acadian Event shows it to be a major subduction-related orogenic collisional event in the north-eastern Appalachian Belt, but absent from Baltica and Greenland. In the British Isles it is patently a proto-Variscan event related to the Rheic Ocean rather than a Caledonian — i.e. Iapetan — event. As such its onset marks the end of the Caledonian Orogeny.

Acknowledgements

A. G. Leslie is thanked for his comments and editing that improved the manuscript. This paper is published by permission of the Executive Director, British geological Survey.

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Book review

Downes, John 2011 *Folds, Faults and Fossils: Exploring Geology in Pembrokeshire*. Llygad Gwalch (ISBN 978-1-84524-172-8; paperback, £8.50)

John Downes has spent a lifetime in teaching and leading fieldtrips. Since retiring as an Open University tutor, he has spent his time in Pembrokeshire, where he has documented many RIGS sites for the county, some of which are featured in this guide.

The guide provides an introduction and brief geological history of south-west Wales that includes an overview of the processes/structures and how they have shaped and influenced the understanding of Welsh geology. Each of the main chapters is divided according to the age and location of the geology, and is prefaced with a brief geological overview of the region. Each includes a stratigraphical column and how the rocks have been used as an economic resource. About 6–12 of the most easily accessible locations are featured in each chapter, where the geology and structures can be observed in detail. Each location includes its OS grid reference, travel directions and useful information on car parking, pubs and other relevant information.

In all there are more than 70, mostly coastal, locations, ranging in age between the Precambrian and the Quaternary, and spanning the nearly 650 million year history of the geology of Pembrokeshire. The vast majority of locations are illustrated with a simple geological map, cross section and line drawing showing geological structures. Additionally, there are more than 30 colour photographs, most taken by the author.

The final chapter is a supplement to the locations and provides details of interesting inland sites that are less well known than the coastal ones. This field guide also has a useful and comprehensive glossary to help support an appreciation of the geological terminology and processes, the inclusion of which suggests that it is aimed at students and walkers who are interested in the landscape and the underlying geology.

This is a nice little field guide, ideally sized for the pocket, which will provide hours of pleasure to the student and amateur geologist alike.

— Pauline Peirce, OUGS Wessex Branch

Book review

Parise, M. and Gunn, J. (eds) 2007 *Natural and Anthropogenic Hazards in Karst Areas: Recognition, Analysis and Mitigation*. London: Geological Society Special Publication 279 (ISBN 978-1-86239-224-3; hardback, 179pp; £70)

'Karst areas' comprise terrain with distinctive landforms and drainage (often underground), mainly originating from solution erosion and commonly developed on carbonate rocks or evaporates (*Penguin Dictionary of Geology*).

This book is a collection of peer-review papers presented at the Second General Assembly of the European Geosciences Union in Vienna, Austria, 24–29 April 2005, and other invited contributions. They highlight the hazards present in karst areas, their recognition, analysis and mitigation, mostly through case studies from a variety of different karst areas around the world.

The book is introduced and edited by Parise and Gunn, who briefly introduce the concept of karst areas as being those that are generally dominated by subterranean drainage, and have a paucity of water flowing at the surface, a consequence of rapid water infiltration underground through discontinuities in the soluble rock mass. They conclude that the consequence's of this are two fold: firstly that 25% of the drinkable water in the world is thought to be contained within these resources; and secondly, that these regional groundwater bodies can easily be contaminated by human activities, which can introduce contaminants from both point sources and dispersed infiltration. They briefly discuss the fact that human activities can easily — and severely — impact karst areas, often irreparably, and conclude that the sustainable management of karst areas and there resources should be further studied to gain a greater understanding of the character of these areas for the benefit of all.

The papers are subdivided in to three key subject areas:

Collapse and subsidence hazards:
This consists of six papers that briefly discuss several topics: the identification sinkholes in Florida by aerial photography (interestingly comparing photographs from 1926 before urbanisation with post urbanisation photographs form 1995 in which 87% of the sinkholes featured in 1926 can no longer be identified); the danger posed by additional anthropogenic loading over known or unknown caves and the safety considerations surrounding building in karst areas; sinkholes in Italy, their definition and the first results of there inventory and analysis; the assessment of cover-collapse sinkholes in south-west Sardinia, complete with a preliminary hazard map; slope instability in southern Italy; and lastly, the magnetic detection of dolines in northern Spain.

Hydrological hazards:
The long-term effect of the flooding of coastal karst geomorphosites in central-east Sardinia in 2004; an attempt to define protection zones around groundwater sources in carbonate aquifers; a discussion on the speed of water flow through the Yorkshire chalk aquifer and the effect of water speed on the deposition of contaminants within the porous matrix of the chalk; the use of stable isotope in sulphates as tracers of natural and contaminant sulphate sources in Sichuan, China; a study on the vulnerability of the Alburni karst system in southern Italy; and finally, the impact of quarrying on karst aquifers in southern Italy.

Managing karst:
This section has two papers. The first paperlooks at the natural and anthropogenic karst hazards present in Jamaica, of which about two-thirds of the landscape is thought to be karst; and the second paper is an interesting look at prehistoric cave paintings in the 'Grande Grotte' cave in Yonne, France, in which the growth of biotic and abiotic calcite formation, and its implications are examined.

This is a specialist publication, which presents well written and interesting papers that the enthusiast can follow. To get the best from them, some of the papers will need some commitment and studying in detail. However, all of the papers can be appreciated at a more basic level as well.

— Mark Appleby, BSC (Open)

Book review

Crawford, Nick, and Anderson, David 2010 *Scottish Agates*. Lapidary Stone Publications (ISBN 978-0-9558-106-1-9; paperback, 202pp, £14.99)

This is a beautifully illustrated and comprehensive introduction to the subject of agates and the art of collecting these fascinating fibrous chalcedony and course grained quartz crystal minerals. The authors have certainly succeeded in producing a comprehensive account of Scottish agates, including an introduction to the use of these agates in jewellery. The authors have achieved the stated objectives of demonstrating the extraordinary breadth of colours and patterns that can be found in Scottish agates.

The book is divided into several chapters, covering a broad introduction to the geology of Scotland (including the part played by plate tectonics), then going on to describe the theories of agate formation, the history of agate collecting and the locations in Scotland where agates can be found, and, finally, describing the techniques used on agates in lapidary. The book's photographs are comprehensive and include about 800 colour images of agates to demonstrate the beauty and diversity of these stones.

I opine that this will be a useful book for anyone with an interest in mineral collecting, and a book that will find favour both with geology students and laymen with an interest in lapidary. It is a book that can be enjoyed by readers with no prior knowledge of geology and I would recommend it to anyone as a good travel companion when visiting the Highlands of Scotland.

— Alasdair Farquharson, LLB (Hons) Dip. Geosciences (Open)

The effects of the spreading of the Central Atlantic during the Middle Jurassic on dinosaur faunas

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Abstract

The spreading of the Central Atlantic is a complex series of events that include a ridge jump to the east and a ridge jump to the west at c. *170Ma and* c. *162Ma respectively. These jumps were influenced by plate interactions as Laurasia separated from Gondwana, although the second jump may have been influenced by spreading in the Gulf of Mexico, which occurred at about the same time. Dinosaur evolution and diversity were influenced by the spreading of the Central Atlantic that split Laurasia from Gondwana. The presence of dinosaurs, from the same taxonomic groups existed in the two regions from the Triassic until the Early Cretaceous, suggests that there continued to be at least some mixing between Laurasian and Gondwanan faunas. This may have been due to the proximity of the continents during the early stages of opening of the Atlantic, island hopping, or other means, enabling limited contact between Laurasia and Gondwana throughout the Mesozoic. Dinosaur faunas did, however, become more isolated and diverse later, in the Cretaceous, due to higher sea levels and seafloor spreading, but some elements of the faunas were still common to both continents. Similarities in faunas between North America and Asia, suggest that there were still links between these regions until the Maastrichtian at the end of the Late Cretaceous. In Laurasia some apparently endemic dinosaur groups (ceratopsians, pachycephalosaurs, therizinosaurs and others) developed as a result of the break up of the continents and do not seem to have had any contact with Gondwana.*

The diversity of dinosaurs has some differences between Laurasia and Gondwana from the Late Jurassic onwards. During the Cretaceous, Laurasian hadrosaurs and ceratopsians dominated the herbivores. Both these groups of ornithischian dinosaurs were able to chew their food, which aided their ability to digest tough vegetation making it possible for them to evolve to be much smaller in size than their Gondwanan counterparts, the titanosaurid sauropods — a surviving group of the giant saurischian hebivores characterised by their inability to chew and by their enormous size.

There is also always the possibility that the apparent differences between the faunas are due to collecting bias and to differences in outcrop exposure in the present-day remnants of these once vast continents. There are certainly a lot fewer localities in the land masses that made up Gondwana as compared to Laurasia.

Introduction

Plate movements in the Central Atlantic

A great deal has been written on the development of the spreading ridge in the North, Central and South Atlantic that split Laurasia from Gondwana. The Gulf of Mexico basin began to form in the Late Triassic as a result of rifting within Pangaea along zones of weakness in the crust, perhaps relating to the lines of collision existed during the formation of Pangaea in the Palaeozoic. Some have speculated that the rifting may have been the result of an extraterrestrial impact, but few geologists support this hypothesis (Stanton 2002; Mickus *et al.* 2009). The relative motions of the continents have been calculated by many authors, reconstructing the plate movements using the geomagnetic isochrons (M0, M25 and M40) for the Early Aptian, Kimmeridgian and Late Bathonian, respectively (Bird and Burke 2006; Bird *et al.* 2007) (Fig. 1, *overleaf*). The Jurassic Magnetic Quite Zone (JMQZ) is about 70km wider in the African JMQZ than in the corresponding area in the North American JMQZ. This suggests that there was a shift in the spreading ridge to the west between isochrons M38 and M32 (164–159 million years ago) soon after spreading began in the Central Atlantic, and appears to coincide with spreading in the Gulf of Mexico and a reorganisation of the positions of the North American and Gondwanan plates (Bird *et al.* 2007).

Between M40 and M25, the Yukatan block appears to have rotated *c.* 22º anticlockwise. This, coupled with the crustal stretching and thinning, opened the subsiding basin to flooding from the Pacific Ocean across central Mexico. The restricted nature of the basin allowed salt deposition over large areas of continental shelf during the Middle Jurassic (Hall and Najmuddin 1994). Between M25 and M0 there was a further rotation, of *c.* 20º anticlockwise, associated with the completion of the formation of the Gulf of Mexico. During the Late Jurassic continued rifting had widened the Gulf of Mexico sufficiently, and opened the Atlantic Ocean enough, to allow adequate circulation, that halted salt deposition.

Sea floor spreading appears to have been initiated by a lithospheric plate event (or mantle plume in the form of a hot spot) beneath the Gulf of Mexico (Bird *et al.* 2005; Bird and Burke 2006). About 170 million years ago there was a shift of the spreading ridge to the east by about 90km (Vogt *et al.* 1971). This was followed 10 million years later by a further 35km shift to the west, which coincided with the rotation of the Yucatan and the formation of the Gulf of Mexico (Buffler and Thomas 1994; Hall and Najmuddin 1994).

The chronology of the break-up of Pangaea and the formation of the Atlantic Ocean is summarised as follows (Bird and Burke 2006):

Triassic (250–206 million years ago)
- 230 million years (Ma) Pangea breakup began
- 230 to 164Ma Plate subduction in western Mexico and stretching of the Yucatan block

Early Jurassic (206–180 million years ago)
- 200Ma Central Atlantic Magmatic Province (CAMP) lithospheric plate event erupts
- 180Ma Seafloor spreading began in the Central Atlantic (Withjack *et al.* 1998)

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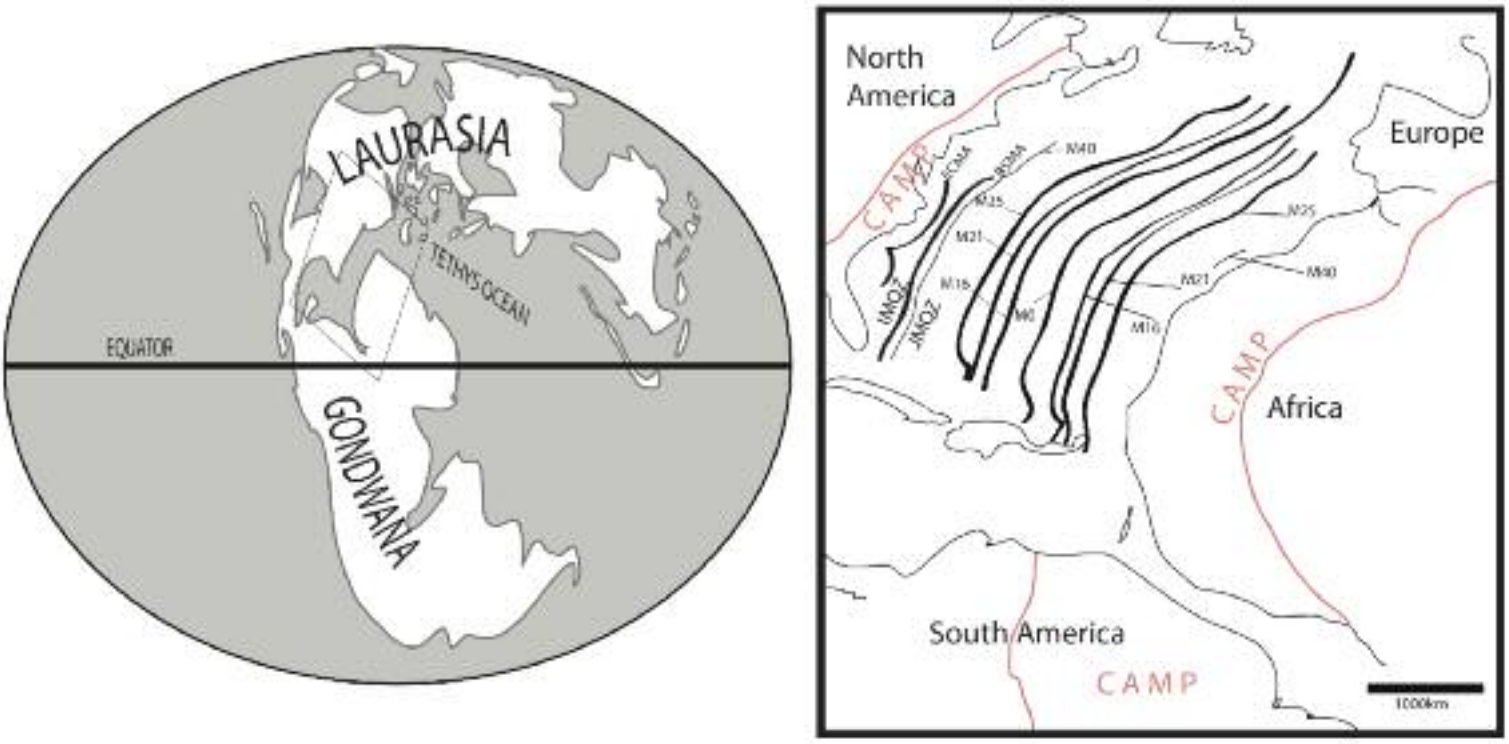


Figure 1 (left) A reconstruction of the positions of the continents during the Middle Jurassic (170 million years ago — based on global reconstructions by Blakey 2011); (right) Early Cretaceous (M0 = 120 million years ago) reconstruction showing geomagnetic isochrones M16 (138 million years ago; Early Cretaceous), M21 (147 million years ago; Tithonian, Late Jurassic), M25 (154 million years ago; Kimmeridgian, Late Jurassic) and M40 (167 million years ago; Bathonian, Middle Jurassic). JMQZ = Jurassic Magnetic Quiet Zone; IMQZ = Inner Magnetic Quiet Zone; BSMA = Blake Spur Magnetic Anomaly; ECMA = East Coast Magnetic Anomaly; CAMP = Central Atlantic Magmatic Province (based on Bird et al. *2005b, and McHone nd).*

Middle Jurassic (180–159 million years ago)
- 170Ma Eastward ridge jump in the Central Atlantic (abandoning African lithosphere on the western flank) (~M40)
- 160Ma Westward ridge jump in the Central Atlantic (abandoning North American lithosphere on the eastern flank) (M32–38)
- ~160Ma Yucatan block began to rotate away from North America, 24º counter-clockwise continental extension (~M32)

Late Jurassic (159–145 million years ago)
- ~150Ma Seafloor spreading in the Gulf of Mexico, 20º anticlockwise rotation of the Yucatan block (M22–23)

Cretaceous (145–65 million years ago)
- ~140Ma Gulf of Mexico formation was complete (M17)
- ~126Ma South America began separating from Africa (M3–4)

Dinosaur distribution

There are only a handful of Triassic dinosaur localities around the world and not very many specimens either (except in particular localities, such as in the Chinle Formation in Arizona, from which several hundred complete individuals of *Coelophysis* have been collected). This makes it difficult to compare the distribution of dinosaur groups of this age around the world in a meaningful way. As a whole, dinosaurs are probably not the best choice of living organism for looking at the relationship between the split of Pangaea and endemism, as these are generally large animals with a poor fossil record — although this is improving each year, and the more we find, the better our understanding of this relationship will become. It is not their size that affects their endemism, but their size does affect their fossil record, as large animals are often missed in small excavations. The dinosaur fossil record is particularly poor from the Triassic, and the Middle Jurassic, from which few dinosaur species are known (Fig. 2, *opposite*).

To look for changes in dinosaur distribution as a result of the opening of the Central Atlantic during the Middle Jurassic, it is necessary to look at dinosaur distribution throughout the time span of dinosaur existence, excluding those that survived the end-Cretaceous extinction.

It is generally thought that there were several groups of dinosaurs that evolved in isolation — such as the therizinosaurs of Asia, and pachycephalosaurs of North America), or even migrated to different parts of the World at different times (such as some sauropods and thyreophorans — and that this may reflect particular events in the tectonic, sea-level and climatic history of the Earth (Holtz *et al.* 2004). It is difficult, therefore, to know whether the absence of a particular group of dinosaurs is because it was never there, or just has not yet been discovered. In other words: can the absence of evidence be taken as evidence of absence? It is also not certain where the majority of coastlines were at any particular time. We may know with a degree of certainty where the continents were relative to each other, but not the extent to which they were covered by water and for how long. During the Middle Jurassic, for example, there was a huge continental sea in North America in which dinosaur footprints were discovered. These dinosaurs were walking on the sediment surfaces some distance seaward of the supposed shoreline (Clark and Brett-Surman 2008). This, of course is impossible unless there were major, short-lived regressions during the time of the inland sea. Shorelines and land bridges are not easily determined with precision.

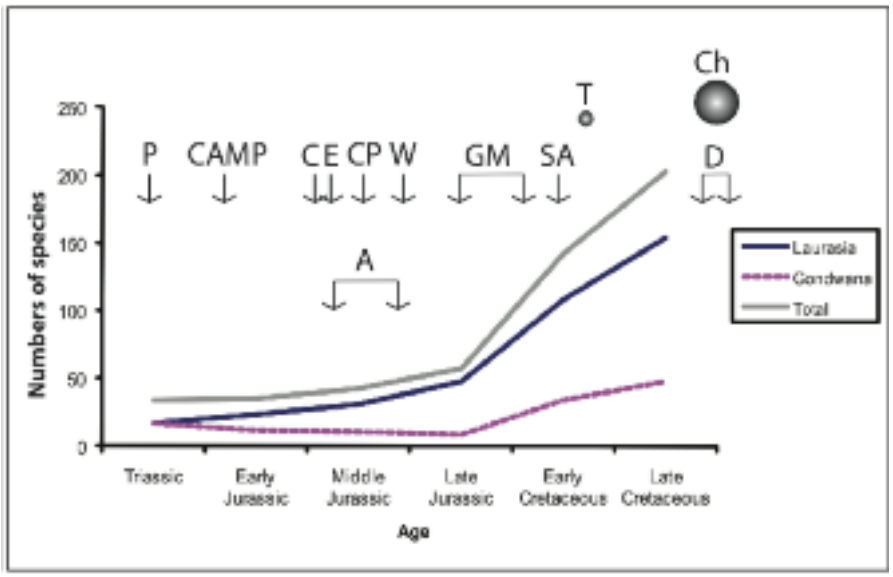


Figure 2 Graph showing the number of species of dinosaurs from the Late Triassic to the Late Cretaceous for Laurasia and Gondwana, as well as volcanic and tectonic activity, and large bolide impacts. (P = Pangaea begins to split; CAMP = Central Atlantic Magmatic Province; C = Central Atlantic seafloor spreading begins; E = Eastward ridge jump; CP = Circum-Pacific volcanism; W = Westward ridge jump; GM = Gulf of Mexico seafloor spreading; SA = South Atlantic opens; D = Deccan lavas erupt; A = Antarctic volcanism; T = Tookoonooka impact; Ch = Chixulub impact.

Methods

The distribution data for dinosaurs was obtained from the global list of dinosaurs produced by Weishampel *et al.* (2004b) with the addition of further more recent examples of Scottish dinosaurs (Clark 2007; Gilchrist 2008). The dinosaur groups used in this study are as follows:

Ornithischia

Ankylosauria
Basal Ornithischia
Basal Thyreophoran
Centrosaurinae
Ceratopsia
Chasmosaurinae
Dryosauridae
Euhadrosauria
Euornithopoda
Hadrosauridae
Heterodontosauridae
Iguanodontia
Lambeosaurinae
Nodosauridae
Pachycephalosauria
Stegosauria

Saurischia

Allosauroidea
Avialae
Basal Saurischia
Brachiosauridae
Camarasauridae
Carcharodontosauridae
Carnosauria
Coelophysoidea
Coelurosauria
Dromaeosauridae
Eusauropoda
Herrerasauridae
Lithostrotia
Micronaria
Neoceratosauria
Neosauropoda
Ornithomimosauria
Oviraptorosauria
Prosauropoda
Saltasauridae
Sauropoda
Spinosauridae
Tetanurae
Therizinosauroidea
Titanosauria
Troodontidae
Tyrannosauroidea

The numbers of genera present during the major subdivisions of the Mesozoic were counted. Data for the Triassic, Early Jurassic, Middle Jurassic, Late Jurassic, Early Cretaceous and Late Cretaceous were recorded for each present-day continent and then combined to provide the listings for the northern continents (Asia, North America, Europe) representing Laurasia, and the southern continents (South America, Africa, India, Australasia and Antarctica) representing Gondwana.

The data from the present-day continents were added together in this way to reflect the Mesozoic distribution of the continents and to identify any potential links between the two major continents at that time. North American faunas were also compared with Asian faunas to see if it was possible to determine the timing of the opening of the northern Atlantic basin. In addition, the Middle Jurassic and Late Jurassic were further split into their respective stages from the Aalenian to the Tithonian and the number of species, localities and formations were counted to provide a more detailed distribution at the time the Central Atlantic was opening using Weishampel *et al.* (2004a) and Clark (2007).

The data were graphically represented in order to visually identify any possible changes in the presence of the above dinosaur groups across the Mesozoic continents.

Results by age

Late Triassic (227–206 million years ago)

During the Carnian to Rhaetian dinosaurs first appeared. Only a few groups of dinosaurs are represented during the Triassic, but the faunas do not appear to be very different between the northern continent (Laurasia) and the southern continent (Gondwana), which developed as a result of the opening of the Atlantic and Tethys seas (Fig. 3A, *overleaf*). In other studies by Holtz *et al.* (2004) — using the same data in a phenetic dinosaurian distribution analysis study with precise locality information for 238 sites as well as 77 distinct taxa — noted the cosmopolitan nature of the distribution of herrerasaurids, coelophysoids, prosauropods and basal ornithischians from the Late Triassic to the Early Jurassic. This agrees with the current study's assertion that the faunas are similar between the Gondwanan and Laurasian regions early in the Mesozoic.

Early Jurassic (206–180 million years ago)

From the Hettangian to the Toarcian, there does appear to be some differences between the faunas in the regions that were to become Laurasia and Gondwana, with some groups surviving one area and not the other, as well as some new taxa appearing (Fig. 3B). In the Laurasian region, basal thyreophorans, neo-

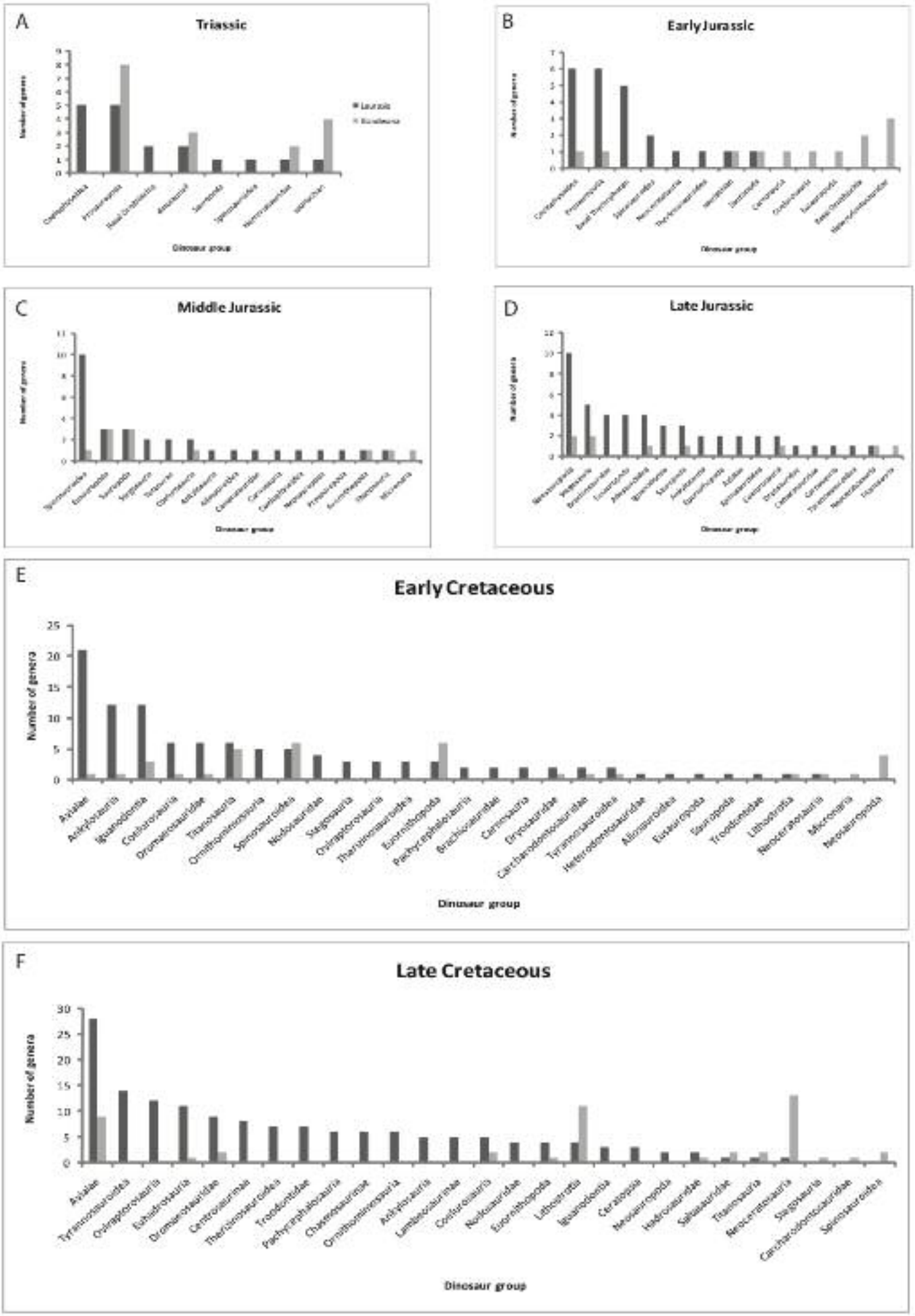

A
Triassic
B
Early Jurassic
C
Middle Jurassic
D
Late Jurassic
E
Early Cretaceous
Number of genera
Dinosaur group
Aviale
Ankylosauria
Iguanodontia
Coelurosauria
Dromaeosauridae
Troodontidae
Ornithomimosauria
Spinosauridae
Nodosauridae
Stegosauria
Oviraptorosauria
Therizinosauroidea
Euornithopoda
Pachycephalosauria
Brachiosauridae
Camosauria
Ornithopoda
Carcharodontosauridae
Tyrannosauroidea
Heterodontosauridae
Allosauroidea
Eusauropoda
Sauropoda
Troodontidae
Lithostrotia
Neoceratopsauria
Micronaria
Metasauropoda
F
Late Cretaceous
Number of genera
Dinosaur group
Aviale
Tyrannosauroidea
Oviraptorosauria
Euhadrosauria
Dromaeosauridae
Centrosaurinae
Therizinosauroidea
Troodontidae
Pachycephalosauria
Chasmosaurinae
Ornithomimosauria
Ankylosauria
Limbeloscaurinae
Coelurosauria
Nodosauridae
Euornithopoda
Lithostrotia
Iguanodontia
Ceratopsia
Metasauropoda
Hadrosauridae
Saltasauridae
Titanosauria
Neoceratopsauria
Stegosauria
Carcharodontosauridae
Spinosauroidea

Figure 3 (opposite page) A series of graphs showing the changes in dinosaur generic abundance of various groups from the Triassic to the Late Cretaceous for Laurasian (dark grey) and Gondwanan (light grey) faunas: A Triassic; B Early Jurassic; C Middle Jurassic; D Late Jurassic; E Early Cretaceous; F Late Cretaceous.

ceratosaurians and therizinosauroideans first appear, and in the Gondwanan region, some basal ornithischians survive and heterodontosaurs, carnosaurs, coelurosaurs and eusauropods first appear (Fig. 4). The other taxa appear to be cosmopolitan: the coelophysoideans, prosauropods, basal saurischians and the sauropoda. This agrees broadly with Holtz *et al.* (2004), if the heterodontosauridians and basal thyreophorans are included in the basal ornithischians, who noted that there remained a similarity in the faunas into the Lower Jurassic.

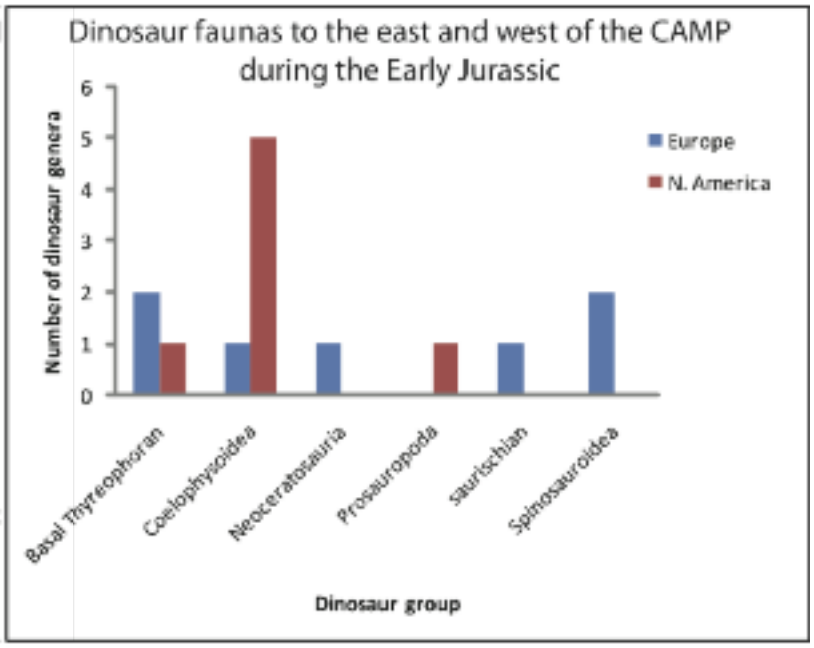


Figure 4 (right) Comparison of faunas to the west (North America) and east (Europe) of the CAMP (Central Atlantic Magmatic Province) in the Early Jurassic.

Middle Jurassic (180–159 million years ago)

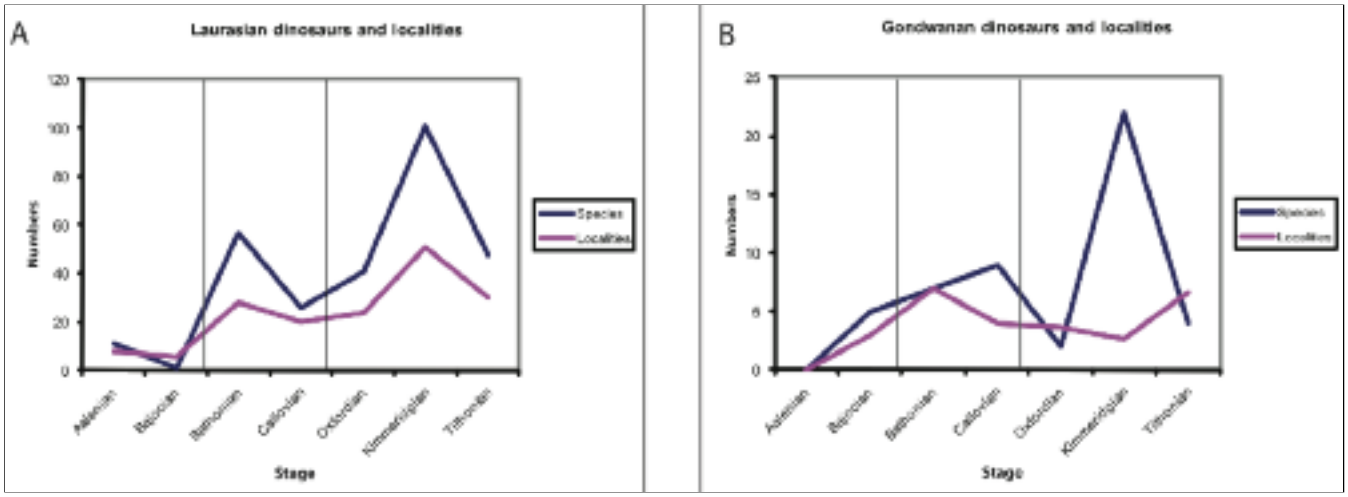
This is the time in which the Central Atlantic is opening, beginning 180 million years ago, as well as the east and west jumps of the Atlantic ridge, circum-Pacific volcanism and extensive Antarctic volcanism. There is a broad correlation of taxa between the northern and southern continental regions from the Aalenian to the Callovian (180–159 million years ago) (Fig. 3C) and only one group of dinosaurs unique to Gondwana — the Micronaria. The differences between Laurasian faunas and Gondwanan faunas include several new taxa such as the Ankylosauria, the Stegosauria, the Tetanurae, the Allosauroidea, the Camarasuridae and the Neosauropoda, in the north and as well as the Micronaria in the south (Fig. 3C). There are also new taxa common to both continents, suggesting that there was at least some communication between faunas: the Euornithopoda and the Titanosauria. The larger number of dinosaur groups represented in the Laurasian region may be an effect of the smaller number of dinosaur-bearing localities in the Gondwanan region (less than 20%).

Holtz *et al.* (2004) noted that there were faunal differences between Europe, Asia and North America plus Africa. It should also be noted that there was a difference between the Asian faunas and North American faunas in the Early Jurassic, as well with only two out of the five taxonomic groups represented in both regions (the basal thyreophorans and the prosauropods).

There are fewer Middle Jurassic dinosaur localities worldwide than there had been prior to and after that time, with less than 20% of the localities than in the Lower Jurassic. This may have been due to fewer discoveries rather than to fewer dinosaurs. However, when the data are looked at for species and localities in the Middle Jurassic by stage, there is greater variation in the numbers of species at different times than in the number of localities (Fig. 5A and B). The number of dinosaurs tends to increase with an increase in the numbers of dinosaurs-bearing localities by a factor of nearly two. Other factors, such as the amount of exposure of rocks of the right age or environment will also have an effect and are beyond the scope of this study. The Kimmeridgian peak is lacking from the locality profile in the Gondwanan faunas, suggesting a genuine increase in species numbers (Fig. 5B), i.e. the increase in species is not due to the increase in the number of localities. The small number of localities in Gondwana at this time, however, makes it difficult to draw too many conclusions about this relationship.

As most of the localities and species of dinosaurs are found in Europe, these were removed to see if that would affect the correlation

Figure 5 Graphs showing the number of species found at different stages of the Middle and Late Jurassic in Gondwana (A), and Laurasia (B). Vertical lines represent the ridge jumps to the east (left) and to the west (right).



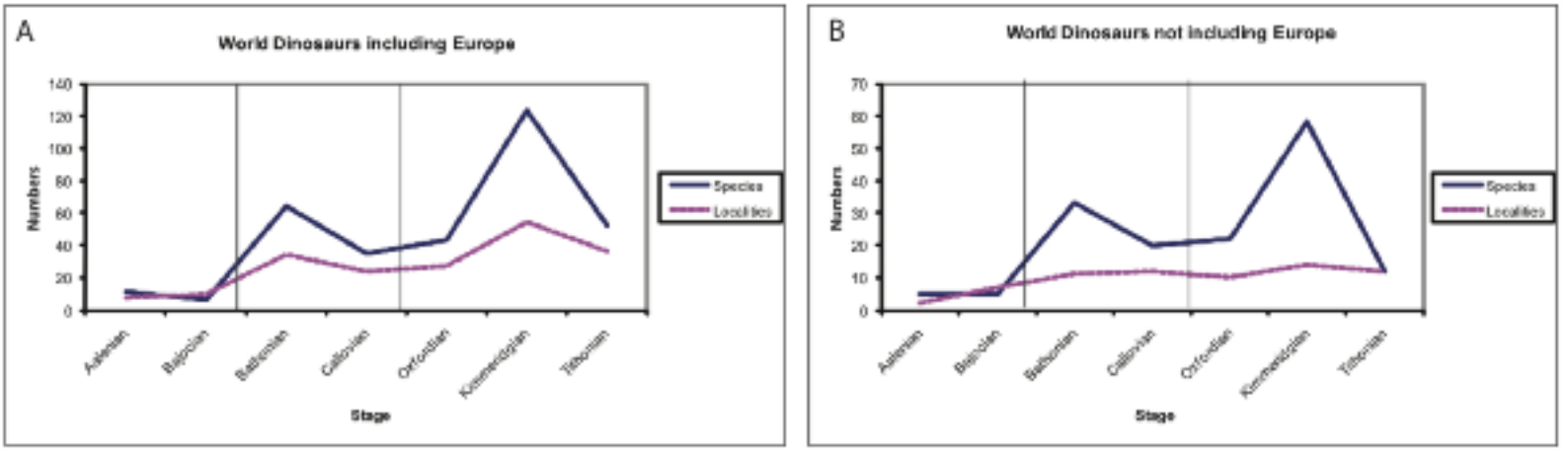


Figure 6 Graphs showing the global number of dinosaur species with the number of localities during the Middle to Late Jurassic (A) and with European data extracted (B). Vertical lines represent the ridge jumps to the east (left) and to the west (right).

between numbers of species with stage (Fig. 6A and B). The resultant graph shows the same two peaks with a dip in the Callovian and Oxfordian and a further reduction in species number in the Tithonian. The localities profile is almost the same as that of the species number profile for the Laurasian faunas including Europe, but the Kimmeridgian localities peak is less pronounced in the Laurasian faunas not including Europe. This supports the idea that the dinosaur numbers may be affected by contemporaneous events rather than being an artefact of the data.

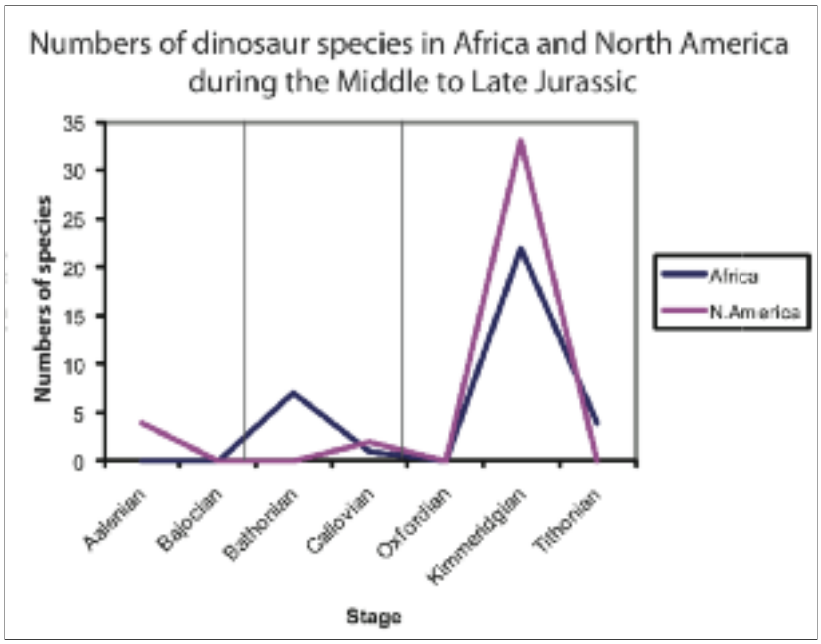
When the African and North American faunas, which are most likely to be affected by the Central Atlantic spreading event due to their proximity to the spreading ridge, are looked at in isolation, the curves match closely (Fig. 7). Although no dinosaur remains are recorded from North America during the Bathonian, and only a few from the rest of the Middle Jurassic, there is plenty of evidence to show the presence of sauropod, ornithopod and theropod dinosaurs from their tracks at 13 localities in the United States and Mexico during the Middle Jurassic (Weishampel *et al.* 2004a).

Late Jurassic (159–145 million years ago)

There is a similarity between the Gondwanan and Laurasian faunas, but there are a lot more groups represented in the northern continent than in the south during the Late Jurassic (Fig. 3D). The main differences are with the types of sauropods: eusauropods, camarasaurids and brachiosaurids in the Laurasia; and titanosaurids in the Gondwana, with neosauropods common to both regions. Ornithopods such as dryosaurs, euorninopods and iguanodons are also found only in the Laurasian region. The carnivorous saurischians of Laurasia include primitive birds (Avialae), spinosaurs and tyrannosaurs. Due to the very low number of dinosaurs in the southern continent at this time, it is difficult to draw too many conclusions from this as there are only a few localities presently known in the Gondwanan region.

There are a few groups that seem to survive and flourish during the Tithonian. Stegosaurs increase from six species in the Kimmeridgian to eight species in the Tithonian, neosauropods lose one species from 14 to 13 and tyrannosaurids stay level at one species, but survive well into the Cretaceous (Fig. 8, *opposite*).

Figure 7 Graph showing data for African and North American dinosaur species during the Middle to Late Jurassic. Vertical lines represent the ridge jumps to the east (left) and to the west (right).



Cretaceous (145–65 million years ago)

Although the number of known localities increases substantially for the Cretaceous, the number of Gondwanan localities increases only slightly compared to those of the Laurasian continental region and represents only about a quarter of the Laurasian localities. This is reflected in the numbers of dinosaur species as well as by the fact that there are only a third of the number of species represented in the southern continent in the Early Cretaceous (145–100 million years ago) and less than a fifth in the Late Cretaceous (100–65 million years ago) (*see* Fig. 2). Most groups seem to be present in both Laurasia and Gondwana, but there are a few dinosaur groups that appear endemic to the Laurasian faunas especially in the Late Cretaceous (Fig. 3E and F). However, nodosaurs, iguanodonts, lambeosaurs, pachycephalosaurs, ceratopsians, therizinosaurs and troodontids seem to be present only in the northern continental region. In the southern regions, spinosaurs, carcharodontosaurs, and stegosaurs survive into the Late Cretaceous after becoming extinct in the north. Titanosaurs were essentially Gondwanan, although a few seem to have been able to island-hop to southern parts of Laurasia, perhaps from northern Africa

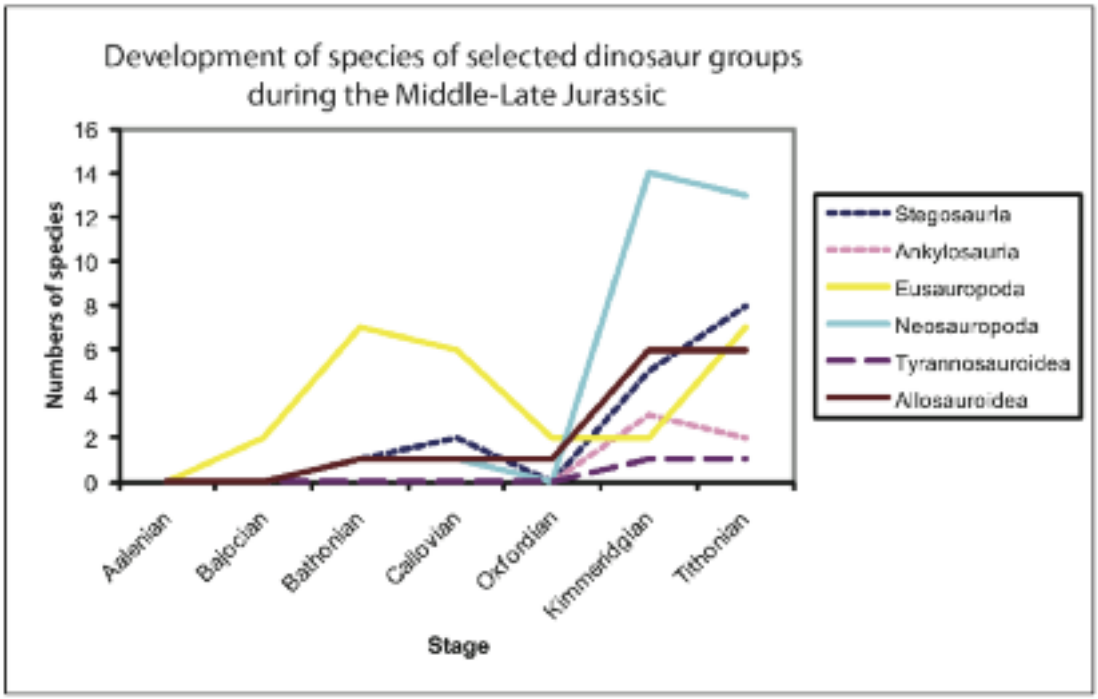


Figure 8 Numbers of species of several groups of dinosaurs during the Middle to Late Jurassic. Two from the ornithischians (Stegosauria and Ankyosauria); two theropods (Tyrannosauroidea and Allosauroidea); and two sauropods (Eursauropoda and Neosauropoda).

via Europe to the southern United States and Asia (Benton 1996; Upchurch *et al.* 2004). There is even a titanosaur tooth from Scotland (Barrett 2006), indicating that they had a foothold in Laurasia as early as the Middle Jurassic.

Discussion and conclusions

During the Early Jurassic, *c.* 200 million years ago, the CAMP lithospheric event was occurring along what was to become the line of the opening of the North Atlantic, producing vast amounts of lava. The CAMP could have been a barrier to faunal mixing between North American and eastern regions (Europe and Asia); however, the data do not appear to support this conclusion, as both regions have dinosaur taxa in common, such as basal thyreophorans and coelophysoideans. The main difference is that the prosauropodans appear to have died out in Europe, but not in North America. But absence of evidence may be a problem of collecting specimens rather than reflecting a real difference.

As the Middle Jurassic was the period of the opening of the Central Atlantic, it can be suggested that this had an influence on the speciation and extinction rates of dinosaurs. There are two peaks of increased numbers of dinosaur species in Laurasia (*see* Fig. 5B): one in the Bathonian (165–168 million years ago) and the other in the Kimmeridgian (151–156 million years ago). This represents an increase in dinosaur speciation occurring after the eastward (*c.* 170 million years ago), and the westward (*c.* 160 million years ago) ridge jumps in the Central Atlantic, respectively, as well as in the movement in the Yucatan block (*c.* 160 million years ago). At the Bathonian/Callovian boundary (*c.* 170 million years ago) there is a major carbonate productivity crisis in western Tethys due to a global marine transgression (Brigaud *et al.* 2009). There are also indications from the palaeoflora that conditions became more humid (Chamley 1989).

There are changes in the types of dinosaurs that are recognised prior to the Oxfordian dip to those after. Dryosaurs appear in the Kimmeridgian and most other ornithischians increase in numbers of species. This may in part be due to changes in the modes of feeding of the herbivorous dinosaurs after the extinction of the prosauropods before the Bathonian (Buffetaut 2005), but also as a result of small extinctions opening up new niches driving speciation. Sauropods became the 'high-browsers' and other herbivores (ornithischians) the 'low-browsers' (Fastovsky and Smith 2004). The circum-Pacific volcanism at that time may have contributed to higher pCO_2 levels, leading to acidification (Brigaud *et al.* 2009).

The pre-Oxfordian extinction and post-Oxfordian speciation dinosaur events are also reflected in the marine realm. An increase in extinction rates for agglutinated foraminifera during the Callovian to Oxfordian (Kaminski *et al.* 2010), and a post-Oxfordian speciation is recorded in marine nannofossils (Roth 1987). There is no evidence for extraterrestrial bolide impacts at this time (MacLeod 1998), so this is unlikely to have been the cause. This effect also seems to be reflected in the dinosaurs of the southern continents (*see* Fig. 5A). The increased volcanism during this period combined with the opening and flooding of the Central Atlantic may have affected the levels of greenhouse gasses and well as producing partial barriers to faunas in both regions, and otherwise influenced the diversity of the dinosaur faunas of Laurasia and Gondwana. Whatever the cause, it appears that the extinction during the Callovian to Oxfordian had a global influence, as it can be recognised in Asia as well as in the circum-Atlantic region (Fig. 9, *overleaf*).

The Tithonian dinosaur extinction seems to have wiped out many of the species that developed during the Kimmeridgian and seems to be reflected in the evidence from the circum-Atlantic continents. This extinction is most noticeable at the species level (Figs 5, 6, 7, 8 and 9). Much discussion of this extinction has led researchers to conclude that it is not a significant extinction, because the dinosaur families persist across the Jurassic–Cretaceous boundary (Hallam and Wignall 1997). In terms of the numbers of species present in the Kimmeridgian

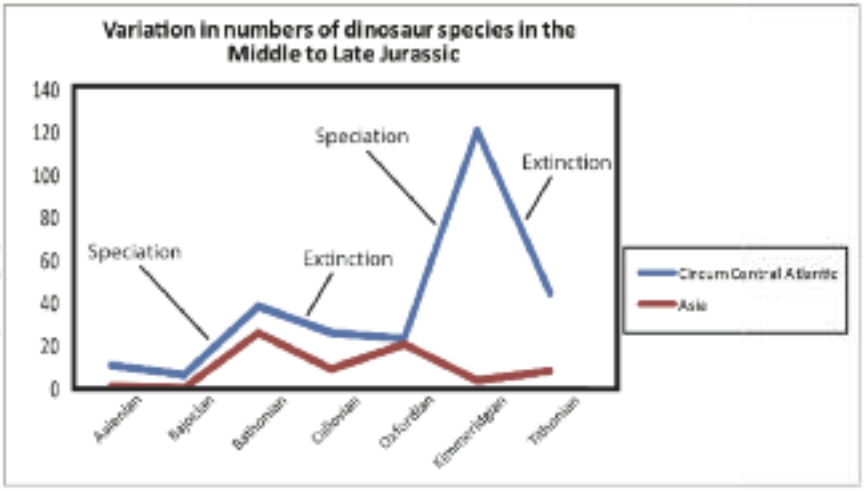


Figure 9 Variation in the numbers of dinosaur species in the Middle and Late Jurassic showing periods of speciation and extinction in the faunas close to the Central Atlantic as compared with the Asiatic faunas.

compared to the number in the Tithonian, there is certainly a significant change. The Tithonian extinction is a recognised extinction that affected the marine realm as well, although this appears to have been a regional, rather than a global, event (Hallam 1986; McCann 2008). This conclusion is supported by the dinosaur data where the Asian dinosaurs do not exhibit the same speciation and extinction profile in the Late Jurassic, despite following quite closely during the Middle Jurassic (Fig. 9).

The Serra Geral flood basalt eruption has often been quoted as the cause of the Tithonian extinction, but according to isotope dating, the eruption occurred somewhere between 120 and 130±5 million years ago just before the opening of the South Atlantic Ocean and well after the Tithonian extinction (Rampino and Stothers 1988). The timing of the Antarctic basaltic eruptions does seem to overlap with the whole of the Middle and Late Jurassic from *c.* 174±8 to 151±18 million years ago (Rampino and Stothers 1988), and hence may have had an influence on the extinction. There do appear to be some impact craters that coincide with the Tithonian extinction, but they are very small, only increasing in size and abundance later into the Cretaceous and hence are not thought to have had a significant contribution to the Tithonian extinction event (MacLeod 1998). The largest at this time is the Tookoonooka impact crater in Queensland, Australia, which is estimated to have been formed between 133 and 112 million years ago in the Early Cretaceous (it is about 60km in diameter, which is about a third of the size of the Chixulub crater that is thought to have contributed to the demise of the dinosaurs at the end of the Cretaceous) (Gorter 1998; Gostin and Therriault 1997).

Europe became an archipelago of islands in the Early Cretaceous. In this region some dinosaurs grew to about 10% of the weight of their relatives elsewhere (Benton 1996), perhaps in response to a gene-encoded response to environmental stress, such as limited food resources in a space-restricted area such as an island. Marine transgressions and continental drift split the dinosaur faunas, isolating them in the Late Cretaceous. Despite this, many groups still seem somehow to have been able to travel from Gondwana to Laurasia, despite the widening bodies of water between them, perhaps by some ephemeral landbridges. It was not only the titanosaurs — which previously existed in Scotland during the Middle Jurassic (Barrett 2006) — but also the carnivorous abelisaurids that were able to travel across the Tethys Ocean to southern Europe (Benton 1996).

It is difficult to be certain of cause and effect when the margins of confidence of the isotopic dates for the volcanic rocks are greater than the length of some of the stages in the Jurassic. The dinosaur data are also limited by the number of species and specimens found; by the inherent problems of dealing with terrestrial deposits that are prone to erosion; and by the limitations of collecting large animals that require large excavation areas for one animal, compared to studying marine microfossils, which tend to occur in vast numbers in small samples. The precise dating of terrestrial rocks is also not as precise as the dating of marine rocks due to the lack of good zone fossils, unless there are some intercalated volcanic rocks. Having said that, there does appear to be some correlation between the various events associated with the opening of the Central Atlantic, such as volcanic activity and marine transgressions, and changes in the numbers of dinosaur species. Endemism, speciation and extinctions of various dinosaur groups in both Laurasia and Gondwana correlate with the splitting of Pangaea as it progressed throughout the Mesozoic.

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Book review

Wangen, Magnus 2010 *Physical Principles of Sedimentary Basin Analysis*. Cambridge: University Press Cambridge (ISBN 978-0-52176-125-3; hardback, 544pp; £88)

This book is about quantitative modelling of sedimentary basins and is aimed at postgraduate-level study, research and the oil industry. The purpose of the book is to show how models work with real data and to enable the student to build his or her own models. A good understanding of mathematics is required to follow the development of the models. Third-level OU Earth Sciences students will recognise some of the basic equations and understand the geological principles and processes used in the models.

The book has chapters on properties of porous media, linear elasticity and continuum mechanics, compressibility of rocks and sediments, burial histories, heat flow, subsidence, rheology, flexure of the lithosphere, gravity and gravity anomalies, quartz cementation of sandstones, overpressure and compactions, fluid flow and wells.

There are test exercises with solutions and demonstrations on how to produce results with MATLAB and Octave.

— Lyn Relph

Book review

Gloaguen, R., and Ratschbacher, L. (eds) 2011 *Growth and Collapse of the Tibetan Plateau*. London: Geological Society Special Publication 353 (ISBN 978-1-86239-326-4; hardback, 255pp; £90)

The Tibetan Plateau featured prominently in S269's module *The Dynamic Earth* (1997) and I understand that this is largely repeated in S279; it also featured in S339 (1990). Many readers will have faced the enormous questions raised in these texts: Did the rise of Tibet set up the present monsoon system? If so, did it 'cool the world'? Is the concentration of CO^2 in the atmosphere primarily controlled by mountain uplift? Why is this far the largest plateau on earth, perhaps the largest area of high land that has ever existed on earth? When, at what stage, in the accretion of Gondwana terranes culminating in India onto the northern continent, was Tibet uplifted? Can studies of movement on faults help? Can fossil leaves point to climatic regimes and to palaeo-altitudes? What exactly were the ways in which the terranes accreted? Is uplift still exceeding erosion? Is there more to be understood from Tibet about continental collision and crustal thickening?

This Geological Society Special Publication will not, I think, help a great many OU past or present students. The articles are all extremely technical and difficult to read. But the editors in their introduction helpfully explain the main points, and these are indeed important. "The first group of papers concern the early Plateau evolution; research appears to promote consensus that the Plateau had a pre-India–Asia collision topographical elevation and the E-striking, pre-existing suture zones were preferably reactivated during Plateau development." The first deformation event occurred at *c.* 30Ma, and the accretion of the Lhasa block to Asia had no effect on eastern Tibet. Significant crustal thickening occurred before the India–Asia collision. Peak metamorphic conditions were reached in the Eocene, closely following the initiation of the India–Asia collision. Post-Miocene clockwise block rotations are inferred in south-eastern Tibet.

"The second group of papers deals with geophysical surveys aiming to localize potential mid-crustal flows in Tibet and the kinematic interpretation of grabens and strike-slip fault zones in terms of flow." Low-velocity zones observed in the HI-CLIMB seismic experiment are associated with active grabens. The upper mantle beneath northern Tibet is slower, less dense, and warmer than the mantle under southern Tibet; this could provide isostatic support for the high elevated, albeit thinner, crust in northern Tibet. There is a petrophysical change at 30-40km depth, perhaps the interface between the felsic upper crust and ore mafic lower crust. The distance of underthrusting by the Indian plate may cause the northward deepening of the 410km and 660km discontinuities.

"The third group of papers describes the active evolution of the Tibetan plateau." Climatic and tectonic signals are hard to discriminate in the whole Pamir-Tibet-Himalaya orogenic system. Uplift is concentrated in fault systems but there is also regional uplift in areas devoid of mapped faults. Ongoing crustal thickening may be triggered by mid-crustal flow in the area of the Qinling orogen. Erosion rates of 2–6mm/a along the eastern edge of the Plateau implies strong and recent drainage reorganisation. There is difficulty in separating the signals of climatic and of tectonic forcing from fragmentary records. Carefulness is called for when interpreting proxies for climate. There is a distinct interplay between non-climatic and climate-triggered land-forming processes that affected the depositional environment. The often forgotten lithological factor plays an important part in the geomorphological analysis of active orogens. No relationship was found between uplift and incision under comparable climatic conditions. Larger mass movements occur at lower altitudes, implying that para-glacial effects must be at work.

— Philip Clark, MA (Oxon), BSc Hons (Open)

Palaeogene magmatism and the opening of the North Atlantic

Brian Bell

University of Glasgow

Abstract (only)

During the early Palaeogene a major rifting event took place in the North Atlantic region, resulting in magmatic activity over an area extending from north-east Canada, across Greenland and the British Isles, as far as mainland north-west Europe. Huge volumes of magma were generated, giving rise to extensive lava fields, thick accumulations of pyroclastic and volcaniclastic materials, intrusive complexes interpreted as congealed magma chambers, and significant amounts of underplated material.

The various volcanic materials provide valuable clues about the style of the extrusive activity and associated fractionation processes. Dr Bell's talk provided an overview of the field and geochemical evidence, and of what it tells us about this intense period of magmatic activity that, ultimately, led to the development of a new ocean spreading centre forming at the end of the Palaeogene.

North of the Suture: 'Stitches in time' — an overview

Stuart Monro

Scientific Director, Our Dynamic Earth

Dr Munro presented a slideshow as a general summary of the nine papers presented at the symposium.

Book review

Smith, Alan 2010 *Lakeland Rocks – An Introductory Guide*. Keswick: Rigg Side Publications (ISBN 978-0-95446-793-7; paperback, 84pp; £4.99)

This is another (number 4) in Alan Smith's A5-format, very readable books on the Lakeland, and again of value to earth scientists and interested lay readers.

Following a two-page introduction from Alan there is really only one 'chapter' as such, since the divisions are the rock types themselves. He begins with the Skiddaw Group — Lakelands oldest rocks — and then from page 10 to page 32 describes various volcanic rocks.

Pages 33 to 70 cover the Silurian into the early Devonian and the extensive intrusive igneous rocks.

Then, after two pages on the more distinctive metamorphic rocks, there are eight pages on the Carboniferous and Permian formations, which largely encircle the central 'dome' of older rocks in the Lake District.

The end of the book has a useful Glossary of Terms used, and some suggestions for further studies.

The centre pages have a useful map of the Lake District Geology, with a colour key to specific localities. Apart from the cover photographs of tuffs at Coniston, columnar andesites near Gosforth and Eyecott andesites, there are 124 full-colour photographs, which alone make this book worth much more than its modest price. (One wonders just how many wonderful photographs the author has taken to date of Lakeland — what a superb collection). He also includes four useful diagrams: a simple classification of the common igneous rocks; a geological timescale; surface exposures of the granite batholith; and the minor intrusive dykes and sills.

Altogether a worthy and delightful addition to the three previous books in the series. If you haven't already acquired this little treasure, add it to your next present list or buy it for yourself. You really do not want to miss it.

— Norma Rothwell, OUGS Vice President

Editor's notes to contributors

Following are guidelines for the submission of articles to the *OUGS Journal*. The principal theme encompassed within these guidelines is 'please keep it simple'. Let your editor do his job and please do not try to simulate, emulate or reproduce the page layout of the *Journal*. I have dedicated page-layout software (QuarkXPress) to do this and any special formatting, special characters and embedded illustrations that you include in a word-processing document can be lost (at best) or seriously confuse and crash (at worst) my iMac or the QuarkXPress software when I import it into the layout.

If your article contains special characters (such as mathematical symbols), please draw these to my attention (I will probably spot them anyway) so that I can import them properly with the glyphs menu in QuarkXPress.

Here are the basic guidelines. I will contact you about any queries that arise when I read your article. I will send you an edited version, showing you any changes that I have made and raising any queries or requesting any missing information.

Guidelines for *OUGS Journal* articles

As *OUGS Journa*l Editor I do not want the publication of your paper to be more work than is necessary for you (or for me!). Your paper need not be more than about 1,500 to 4,000 words in general, but I leave the length up to you to suit the material.

Regarding papers from the presenters of lectures at the OUGS Symposium, all OUGS members are grateful to you for presenting a talk at the OUGS Annual Symposium, and for agreeing to submit a version of your talk for publication in the *Journal*. The purpose of this is to make your information available to OUGS members and others who could not attend the symposium. As OU students and OUGS members we enjoy hearing and learning the information these symposia bring to us.

All that is necessary is the following:

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• Each illustration, chart, graph, map or other illustration as a separate digital file in high resolution: 350dpi minimum for colour or half-tone images; 1400dpi for line illustrations. Tables composed in Word or Excel are fine, as they are just text. A rough guide to the number of figures in an article is 10 to 15. Obviously as a symposium presentation speaker you might have shown numerous slides, so please use your best judgement on the number to include with the paper to be published — again usually 10 to 15 is a rough guide. *Please note that figures are normally printed in greyscale in the* OUGS Journal*, except Moyra Eldridge Photographic Competition winners' photographs.*

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